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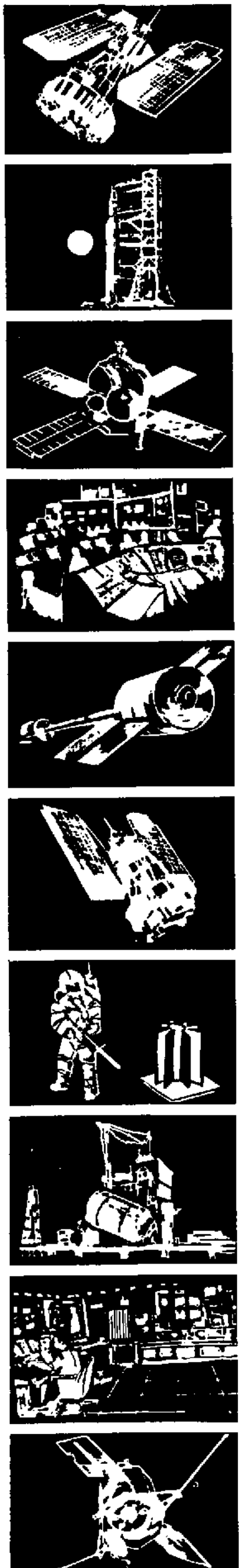

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FINAL REPORT

MINI-BRAYTON HEAT SOURCE ASSEMBLY DESIGN STUDY

VOLUME I

SPACE SHUTTLE MISSION

GENERAL ELECTRIC

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FINAL REPORT

MINI-BRAYTON HEAT SOURCE ASSEMBLY

DESIGN STUDY

Performed Under

Contract NAS 3-16810

FOR

NATIONAL AERONAUTICS & SPACE ADMINISTRATION
LEWIS RESEARCH CENTER
21000 BROOK PARK ROAD
CLEVELAND, OHIO 44135

VOLUME I

SPACE SHUTTLE MISSION

ENERGY SYSTEM PROGRAMS
SPACE DIVISION
Valley Forge Space Center
P. O. Box 8661, Philadelphia, Penna. 19101

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SECTION 1

INTRODUCTION

This report summarizes the results of the Mini-Brayton Heat Source Assembly design study. The study has been performed for the NASA Lewis Research Center under contract NAS-16810.

1.1 OBJECTIVES

The objective of this study was to develop conceptual design definitions of a Heat Source Assembly (HSA) for use in nominal 500 watt electrical (W(e)) 1200 W(e) and 2000 W(e) Mini-Brayton isotope power systems. The HSA is an independent package which maintains thermal and nuclear control of an isotope fueled Heat Source (HS) and transfers the thermal energy to a Brayton Rotating Unit (BRU) - Turbine-Alternator-Compressor power conversion unit.

1.2 SCOPE

The program was divided into the following four major tasks.

I. Safety Study

II. Conceptual Designs

III. Design Definitions

IV. Minimum Weight Conceptual Design

Volume I of this final report contains the results of Tasks I, II and III. Volume II is devoted to the Minimum Weight Concept developed during Task IV.

The safety study focused on the general safety problems associated with an isotope fueled Mini-Brayton system. The purpose was to develop safety design requirements and guidelines consistent with a space shuttle launch, which must be factored into the HSA designs. The manned space shuttle was selected as the reference mission since it imposes the most stringent safety requirement and represents a likely launch vehicle for future missions. Emphasis was placed on thermal control, radiation protection and blast and fragmentation protection. Space shuttle integration considerations, hazards, and potential accidents were identified. A preliminary functional flow analysis for the baseline shuttle mission encompassing the time frame between fabrication and recovery of the Heat Source, was generated to facilitate this. The output of this investigation was a set of safety design requirements and guidelines to ensure personnel safety through all mission phases; to minimize the potential for accidents; and to preclude release of nuclear fuel to the biosphere in the event of catastrophic accidents or failures.

The purpose of the Conceptual Design Study, Task II, was to develop candidate HSA design concepts for a Space Shuttle mission that satisfy both design and safety requirements.

Concepts for each of the HSA functional components (except for the Heat Source) were studied and the most promising ones integrated into overall HSA concepts. The output was a number of different HSA concepts with an evaluation of advantages and disadvantages of each. The Design Definition, Task III, encompassed more detailed definition of the three most attractive conceptual designs for the Space Shuttle mission. The task included selection of candidate materials, fabrication and assembly studies, thermal and hydraulic performance analysis and structural sizing, and design layouts. Also included in this effort was the definition of Ground Handling and Orbit Handling tools to ensure HSA design compatibility with nuclear handling requirements. Task IV, Minimum Weight Conceptual Design, represented a modification to the original contract and was directed toward a nominal 500 W(e) system for a Titan III C launch to synchronous orbit. Some of the basic ground rules and design requirements that apply to the Space Shuttle mission (Tasks I II and III) are different and consequently have significant impact of the design. The results of Task IV are contained in Volume II.

1.3 MINI-BRAYTON SYSTEM DESCRIPTION

The Mini-Brayton power system is a closed gas loop system consisting fundamentally of five major subsystems: a heat exchanger which accepts the energy from the heat source (this assembly is the HSA), a Brayton rotating unit (BRU) which converts this heat energy into electrical power, a heat rejection system which dissipates the waste heat, a recuperator which enhances system efficiency, and an electrical control system.

The Brayton power conversion system is depicted in Figure 1-1. Energy is added by the Heat Source to the working fluid in the HSHX, shown as Points 1 to 2. The gas leaves the HSHX and is expanded in the turbine, Points 2 to 3. At Point 4, the gas entering the recuperator from the turbine, preheats the gas entering the HSHX and consequently, is cooled before re-entering the radiator.

Heat is rejected from the system in a radiator, Points 5 to 6. After exiting from the radiator the gas is compressed, points 7 to 8, and is returned to the recuperator at Point 9.

Three nominal electrical output power levels--500 W(e), 1200 W(e) and 2000 W(e) are being considered; the system configuration for each of the three power levels is depicted in Figure 1-2. For output power levels greater than 500 W(e), two or three 2400 W (t) HSA's are manifolded in parallel and interfaced with a single power conversion system (defined on Figure 1-1).

The Brayton power cycle has several outstanding characteristics which makes it very attractive for space applications. First, the use of an inert gaseous working fluid allows the cycle to operate over a wide temperature range which provides high Carnot efficiencies; by employing a recuperator, high system efficiencies can be realized. Secondly, the system is adaptable for efficient operation over wide range of power levels which can be controlled by changing the system operating pressure while the turbomachinery size remains fixed. Thirdly, a gaseous working fluid allows the user of simple, self-acting gas bearings, ensuring long component life.

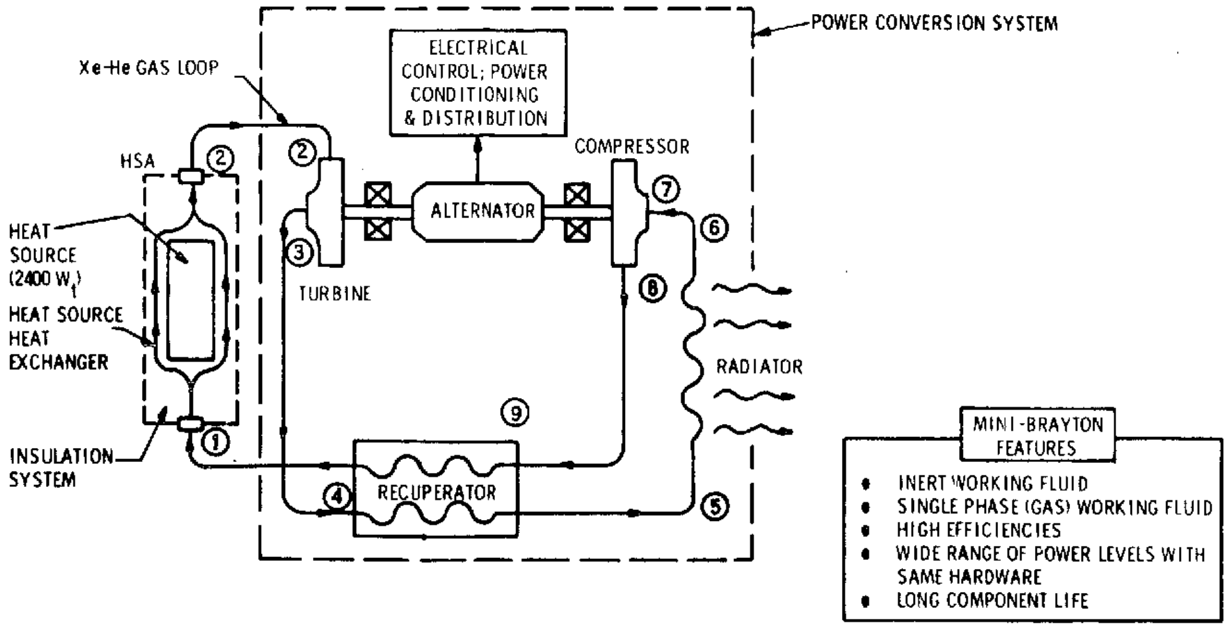
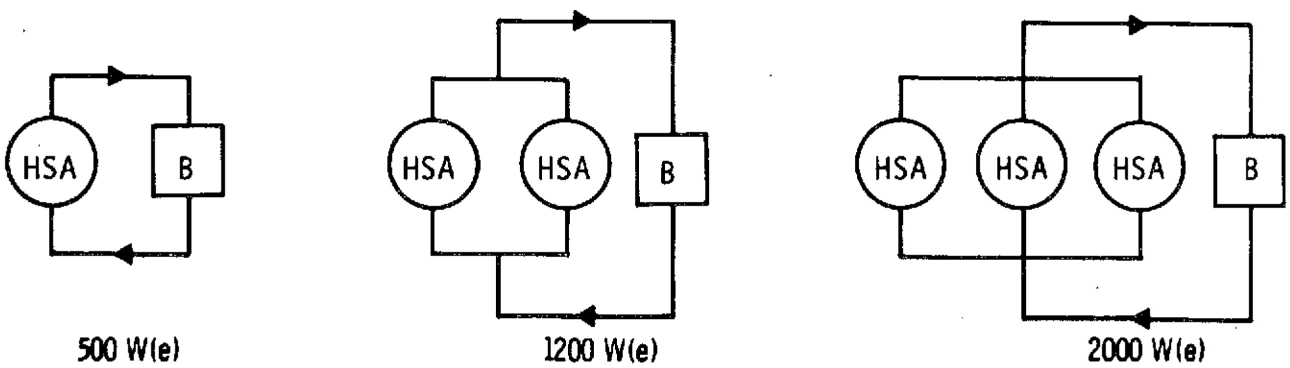


Figure 1-1. Typical Isotope Brayton System

MINI-BRAYTON SYSTEM CONFIGURATIONS FOR VARIOUS OUTPUT POWER LEVELS



- EACH HSA IS AN IDENTICAL, "OFF-THE-SHELF" 2400 W(t) UNIT

NOTE: B DENOTES "POWER CONVERSION SYSTEM" (SEE FIGURE 1-1)

Figure 1-2. Mini-Brayton System Configurations for Various Output Power Levels

An artist conception of an integrated Mini-Brayton Power Module mounted on a typical spacecraft is shown in Figure 1-3. The system is depicted in a normal operational mode, an auxiliary cooling mode on the pad, and in an emergency cooling mode in orbit with the two end doors open.

1.4 HSA DEFINITION AND COMPONENTS

The Heat Source Assembly generates the thermal energy required for operation of the Mini-Brayton System and transfers this energy via a Heat Exchanger fluid loop to the Power Conversion System. The subsystems and respective components which collectively comprise the HSA are listed in Table 1-1.

The Heat Source is fueled with 2400 watts (thermally) of $^{238}PuO_2$ ceramic fuel of 82 percent theoretical density. The design provides positive safety margins for any re-entry up to 11,000 m/sec (36,000 ft/sec) and for all credible accident modes. Since the Heat Source will be flight qualified for the LES 8/9 mission, no additional design or test effort will be required for the Mini-Brayton program. The Heat Source is described in detail in Section 4.

The Heat Source Heat Exchanger transfers heat from the Heat Source to the Power Conversion System by means of a Heat Exchanger and associated heaters and manifolding.

The Auxiliary Cooling Subsystem provides required cooling of the Heat Source and refractory HSA materials during non-operational periods on the launch pad. Coolant is provided at the launch complex.

The Emergency Cooling Subsystem is a passive system that is automatically activated in emergency situations that could result in an over temperature condition of the Heat Source. Such emergencies can be precipitated by unplanned delays in orbit achievement prior to starting up the power system, failure of the Power Conversion System (e.g., loss of radiator integrity, BRU failure, leaks in the gas loop, etc.), unplanned shuttle landing in remote areas

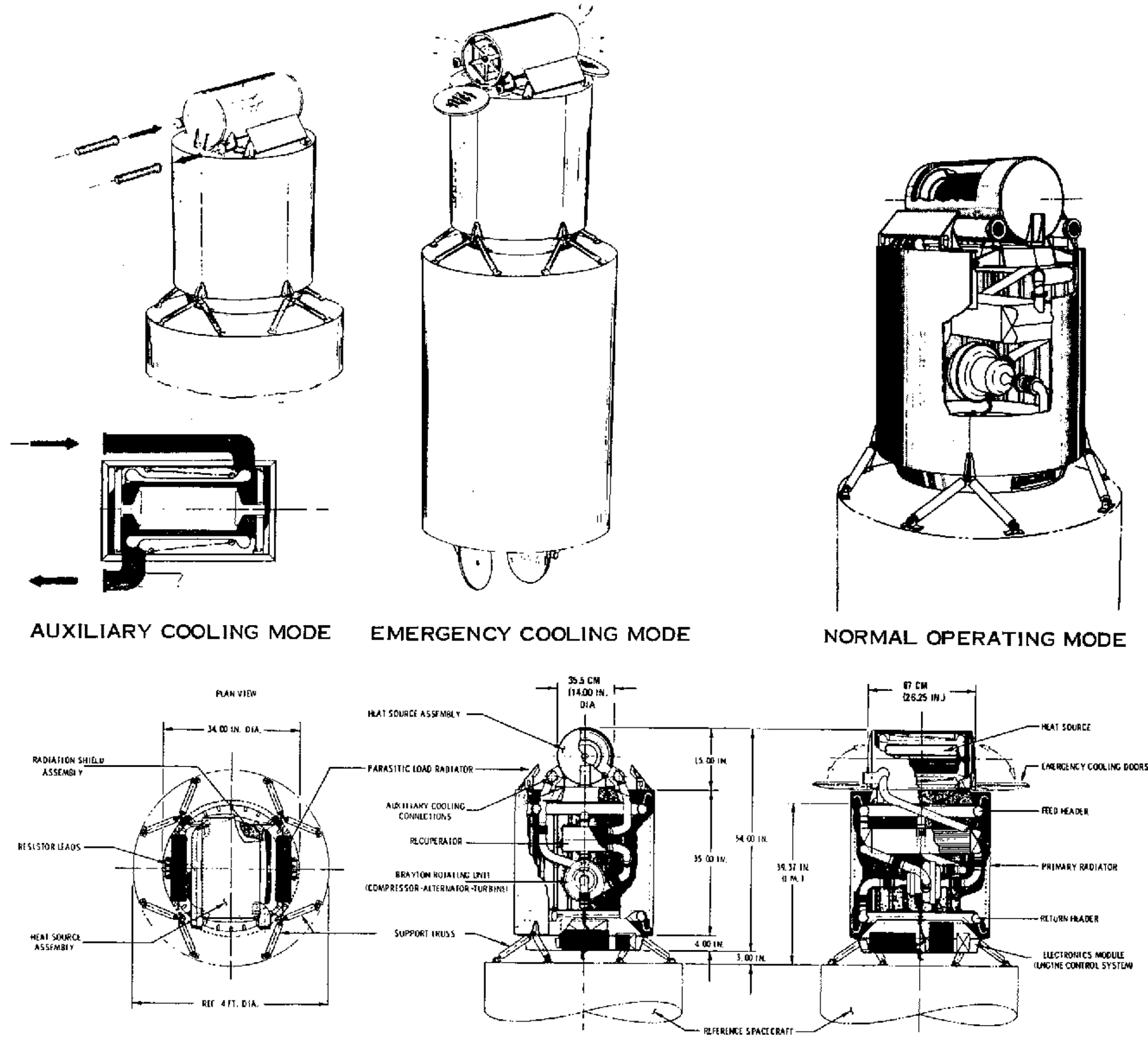


Figure 1-3. Mini-Brayton Power Module (Artist Concept)

where auxiliary coolant is unavailable, etc. The ECS is capable of operating during all mission phases including prelaunch. It is unlikely, however, that the ECS would ever activate during the prelaunch phase since auxiliary cooling is provided and the Heat Source is under positive control.

The Inert Gas System (IGS) is used, if required, during Mini-Brayton prelaunch operational periods at power to protect HSA refractory materials in oxidizing environments. The subsystem utilizes the manifolding and cooling channels of the Auxiliary Cooling System for the concept developed for the Space Shuttle mission, and provides an inert cover gas of the appropriate purity. In essence the IGS is identical to ACS if the same coolant is used for the auxiliary cooling, except that flow rates may be lower (controlled by appropriate valving).

The Heat Source Insulation Subsystem consists of multifoil insulation blankets which surround the HSA structure and minimizes the heat loss from the system. Penetrations through the insulation are provided for the primary cooling system and Auxiliary Cooling Subsystem manifolds. Selection of insulation materials was not within the scope of this contract.

1.5 GROUND RULES

The program guidelines and constraints used as ground rules for the Space Shuttle mission.

1. The Heat Source design developed for the Multi-Hundred Watt (MHW) Radioisotope Generator Program (AEC Contract No. AT(29-2)-2831) shall be utilized.

2. The HSA design shall permit removal of the Heat Source in space for a Space Shuttle mission. (There is no requirement for Heat Source removal in space for the Titan IIIC mission.)

3. A space shuttle launch shall be assumed for the baseline mission.

4. The HSA shall be designed for at least a five (5) year operational lifetime in space.

5. A standard HSA with thermal output of 2400 W(t) (less any heat loss) for use singly in a nominal 500 W (e) Mini-Brayton system shall be designed for the Space Shuttle mission. Two or three of these HSA's are to be manifolded in parallel for a 1200 W(e) or 2000 W(e) Mini-Brayton system respectively.

6. Capability for ground operation of the Mini-Brayton system shall be provided.

7. The Mini-Brayton system shall be shut down during the prelaunch countdown and launch phases of the mission. Startup shall be in orbit.

8. It is assumed that the Mini-Brayton system will not have a requirement for multiple startups after launch. The design however, shall not preclude multiple startup during ground testing.

9. The HSA shall present no radiological hazard for any credible accident mode.

10. The requirement for a two year ground test of a flight configured Mini-Brayton system shall be a consideration in the design of the HSA.

Table 1-1. Heat Source Assembly Subsystems and Components

Subsystem or Component	Symbol	Function	Major Components
Heat Source	HS	Source of Thermal Energy for Power Conversion System (2400 W(t))	• PuO_2 Fuel • Re-entry Protection Systems • Emissivity Sleeve
Heat Source Heat Exchanger	HSHX	Transfers heat from the HS to the Power Conversion System during Normal Operation	• Heat Exchanger • Headers • Manifolds
Auxiliary Cooling Subsystem	ACS	Cools HS during Non-Operational Periods on Launch Pad	• Manifolds • Coolant
Emergency Cooling Subsystem	ECS	Cooling Doors and Associated Devices which Automatically Open the Doors in Emergency Situations (for Space Shuttle mission); Melting insulation for Titan IIIC mission	• Insulated Doors • Hinges and Latches • Emergency Cooling Device (ECD) • Melting Insulation
Inert Gas Subsystem	IGS	Provides Inert Gas Environment (Cover Gas) To Protect HSA Internals in Oxidizing Environments at Power	• Inert Gas • Valving
Heat Source Insulation Subsystem	---	Limits Heat Loss from HS during Operation	• Multifoil Insulation

SECTION 2

SUMMARY

The major conclusions of the study directed toward a Space Shuttle Mission, pertaining to safety requirements, HSA configuration and material selection are summarized in this section.

2.1 SAFETY

2.1.1 SAFETY REQUIREMENTS OVERVIEW

The underlying safety requirement for HSA design and operation, is that no radiological hazard exist during any mission phase or during any credible accident mode. Under steady state conditions, the maximum PICS* iridium/PuO_2 fuel interface temperature should not exceed 1773° K (2732° F). The corresponding Heat Source surface temperature is below 1325°K (2012°F). This PICS/fuel interface temperature limit assures positive containment of the fuel and is based on the fact that, at the present time, experimental data only verifies the long term compatibility of the iridium and PuO_2 fuel up to the indicated temperature. Although sufficient margin should be available for sustained operation at higher temperature, a fuels test program would be required to substantiate this fact.

The principal safety requirements to which the HSA is designed are as follows:

1. Prelaunch
   a. Provide thermal control to maintain all exposed surface areas of the Heat Source Assembly (HSA) below 466.5°K (380°F) to preclude inadvertent ignition of shuttle propellants.
   b. Provide thermal control to limit Heat Source temperatures to safe levels (surface temperature $\leq$ 1325°K (2012° F)) while the power system is non-operational.

*Post Impact Containment Shell (see Section 4.1).

c. A design goal shall be to assure containment of all radioactive material should the Heat Source Assembly or Heat Source be exposed to a fireball or solid propellant fire which may result from a shuttle explosion.

2. Launch and Ascent

   a. Provide thermal control to limit Heat Source temperatures to safe levels, prior to startup while the power system is non-operational (surface temperature $\leq$ 1325° K (2012° F)).

   b. Limit radiation dose levels to the shuttle crew to less than 6.25 MRem/hr. This requirement applies to all mission phases when the HSA is within the shuttle payload bay.

3. Operational

   a. Provide thermal control to limit Heat Source temperatures to safe levels (surface temperature $\leq$ 1325° K) in the event the helium xenon fluid loop fails during normal operation.

   b. The Heat Source shall survive an earth orbital reentry in the following initial configuration:

      (1) A free, unencumbered, Heat Source.

      (2) A free, unencumbered Heat Source Assembly.

      During reentry, the PICS iridium/carbon interface shall not exceed 2372° K (3810° F).

4. Return

   a. Provide thermal control to limit Heat Source temperatures to safe levels (surface temperature $\leq$ 1325° K (2012° F)) during shuttle return from orbit operations:

      (1) While the BRU is non-operational, or

      (2) After removal of the Heat Source from the HSA.

2.1.2 HSA SAFETY DESIGN FEATURES

The MHW isotope heat source used in the Mini-Brayton HSA is being designed to withstand the Titan IIIC liquid and solid propellant fireball explosion over pressure environments. The MHW Heat Source is also designed to survive re-entry at super-orbital velocities with subsequent impact on granite at 89 m/sec (293 ft/sec). Re-entry from a Mini-Brayton mission earth orbital decay will of course impose less severe conditions on the Heat Source. A preliminary analysis indicates that the Heat Source will survive an earth orbital decay of the entire Heat Source Assembly configuration.

For shuttle applications, shielding from blast fragmentation will probably be required within the shuttle payload bay. The requirements for a fragmentation shield are discussed in paragraph 5.4.2.3.

Radiation dose levels to the shuttle crew will be below maximum permissible levels provided that the Heat Source Assembly (in its largest curie inventory for the 2000 Watt(e) Mini-Brayton configuration) is located at least five meters from the crew compartment. Radiation shielding will not be required for a shuttle mission if this requirement is met.

2.2 HSA CONCEPTS

Three candidate HSA concepts which differ only in Heat Source Heat Exchanger design have been developed and are depicted in the sketches of Figure 2-1. One of these is an HSHX consisting of an axial bank of thirty-five (35) 0.95 cm (3/8") OD tubes. The other two HSHX configurations are both plate fin heat exchangers. One incorporates corrugated fins, running axially in the annulus formed by two concentric cylinders. The other plate fin design is similar except that the fins are machined out of the inner cylinder. All three HSA concepts provide for flow of an auxiliary cooling gas directly over the Heat Source in the annulus formed by the outer surface of the Heat Source and the Heat Source Heat Exchanger. Emergency cooling is effected by the automatic activation by the ECD of two flat insulated doors on opposite ends of the HSA. One of these doors also serves as the Heat Source loading door.

During or prior to pre-launch operations, the HSA(s) less the Heat Source(s) will be assembled into the Mini-Brayton Power Conversion system. The Heat Source(s) will be removed from its environmentally controlled shipping cask and loaded into the HSA(s) as late in the countdown sequence as possible.

A detailed engineering drawing of the machined plate fin HSA design is given in Figure 2-2. Both the Heat Source and the HSHX are supported off a cylindrical

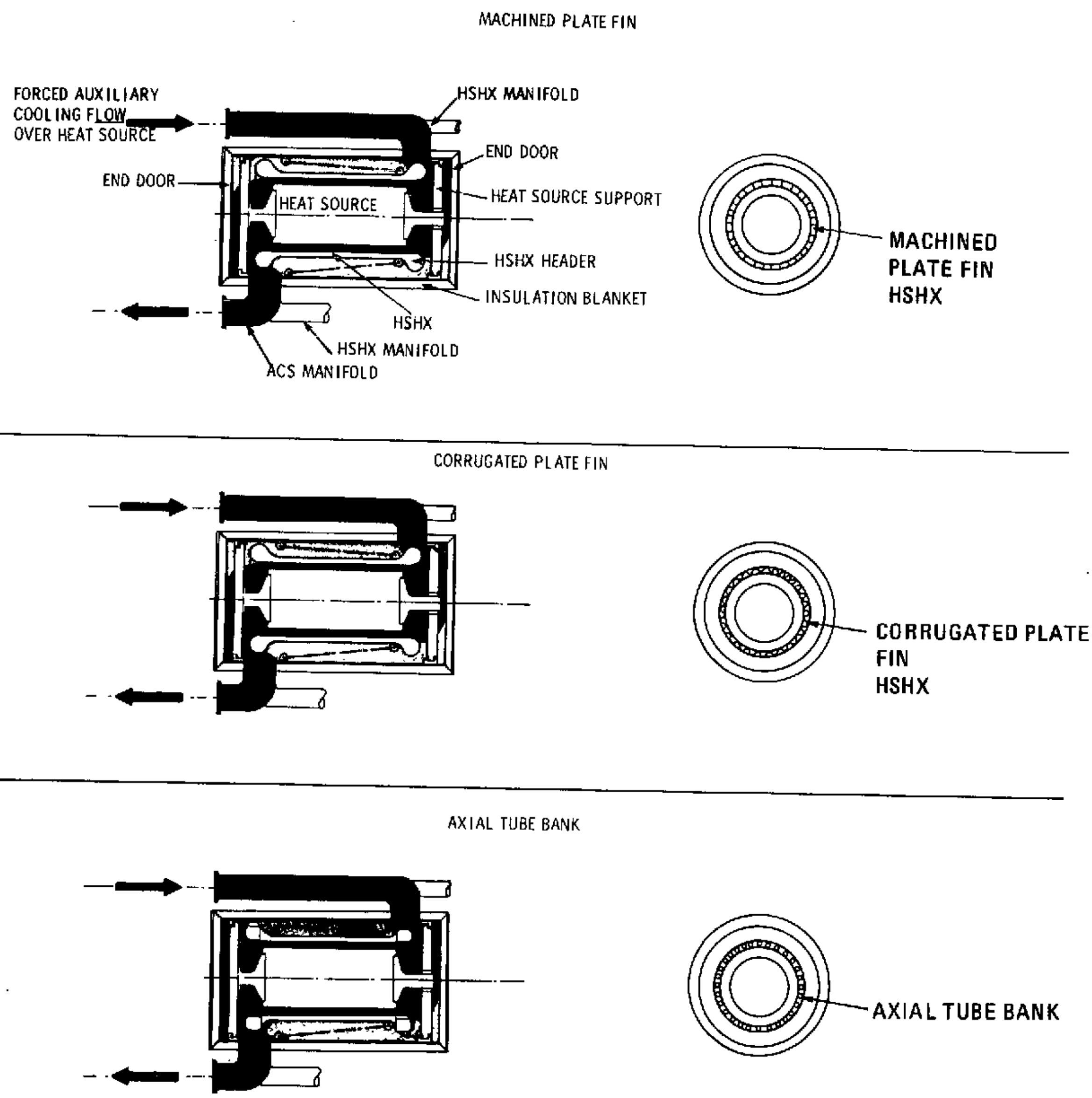


Figure 2-1. HSA Concepts

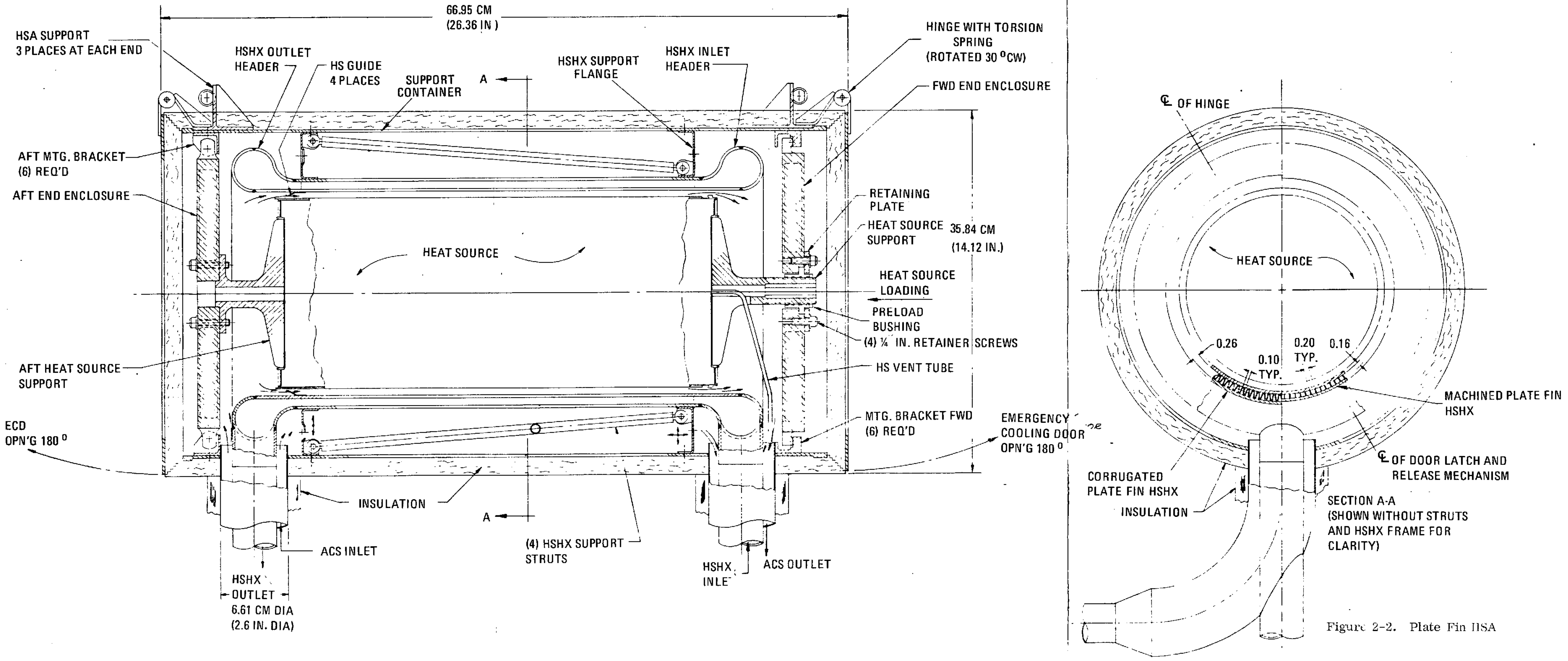


Figure 2-2. Plate Fin HSA

support container which is adjacent to, and inboard of the insulation blanket. HSA support flanges are attached to the container to interface with shuttle support hardware. The HSHX is supported off the container by frames at both ends. Four HSHX tubular support struts provide torsional stiffness and take out longitudinal launch loads on the HSHX. They also are designed to permit thermal expansion of the HSHX during heatup without inducing adverse thermal stresses.

The Heat Source is supported off the support container by forward and aft Heat Source Supports and End Enclosures. The Heat Source Support is similar in design to the MHW support and provides the interface with the Heat Source and the End Enclosure. The End Enclosures, which are very similar in design to the MHW End Enclosures, consist of six spider like radial "I" beams with interconnecting webs. Three retaining screws are provided as a redundant component to release the End Enclosure preload in event of freeze up of the bushing when removing the Heat Source in orbit.

The size, weight and performance characteristics of the three HSA concepts are summarized below. Envelope and weight are not optimized for the designs.

HSA Concept / Characteristic	Tubular HSHX	Machined Plate Fin HSHX	Corrugated Plate Fin HSHX
Envelope			
Length, cm (in.)	66.95 (26.36)	66.95 (26.36)	66.95 (26.36)
Diameter, cm (in.)	35.84 (14.12)	35.84 (14.12)	35.84 (14.12)
Weight, kg (lb)	71.8 (158)	77.7 (171)	78.6 (173)
HSHX Design Pressure, N/cm^2 (psi)	79 (115)	79 (115)	79 (115)
Max Allowable Total Pressure Drop, * N/cm^2 (psi)	0.151 (0.22)	0.151 (0.22)	0.151 (0.22)
Max Heat Source Surface** Temperature, °K (° F)	1319 (1915)	1269 (1825)	1230 (1755)

* For a single HSA in 500 W(e) power system.
**For a HSHX emissivity of $\epsilon = 0.4$.

The tubular HSHX results in the highest Heat Source operational temperature and has the largest number of joints. Both welding and brazing procedures are required in its fabrication.

The corrugated plate fin HSHX results in the lowest Heat Source operational temperature, but provides the least well dimensionally controlled and stable flow channels. Fabrication of the HSHX requires welding and brazing operations.

The machined plate fin HSHX results in a Heat Source operational temperature intermediate between the tubular and corrugated plate designs, has well-defined flow channels, and can be fabricated without brazing. It may be possible to reduce Heat Source temperatures by increasing the number of machined fins. At this point in the program, it is the preferred design.

2.3 MATERIAL SELECTION

Three classes of materials - super alloys, noble metal alloys and refractory alloys were considered for the HSHX. Super alloys were eliminated because they exhibit marginal strength at the HSA operational temperatures and exhibit excessive evaporation loss in vacuum over a 5-year lifetime. Noble metal alloys were eliminated because they are excessively costly and are still in a development stage. The principal candidate refractory alloys considered which satisfy strength and operation environmental conditions were Cb-103, Cb-1Zr, Cb-129Y, T-111 and Ta-10W. These candidates were narrowed down to Cb-103 and Cb-1Zr primarily by considerations of weight and fabricability. Additional long term creep strength data at HSA operational temperatures and further characterization of both materials are required to make a final selection.

SECTION 3
SYSTEM CONSIDERATIONS

3.1 SPACE SHUTTLE INTEGRATION AND INTERFACES (Reference 1)

The baseline mission for this study is a launch of the Mini-Brayton system and recovery of the Heat Source in the Space Shuttle. Since the shuttle is not completely designed yet, interface and integration definition must be considered preliminary.

3.1.1 GENERAL

The Mini-Brayton system is housed within the 15-foot diameter, 60-foot long shuttle payload bay. Multiple standardized attachment points are located in the payload bay to structurally support shuttle payloads.

The orbiter has the capability to expose the entire length and full width of the payload bay, providing an unobstructed 180 degree lateral field of view. Nonstructural payload service panels are placed at discrete locations in the payload bay wall for GSE service access. Payload panels designed to service a particular payload can replace the blank service panels. Payload checkout and caution and warning systems are provided in the crew compartment.

A shuttle remote Manipulator System consisting of a pair of remote manipulator arms is provided for deployment and retrieval of a payload such as the Mini-Brayton system. Payload engagement is accomplished through terminal devices on the end of each arm.

Electrical power for shuttle payloads is available from the orbiter electrical power system. An electrical energy allowance of 50 kilowatt-hours of nominal 30 Vdc power is dedicated for payload support with energy in excess of this allocation being mission dependent and capable of being supplemented by additional consumables to the orbiter fuel cells and/or by independent payload systems.

3.1.2 PAYLOAD BAY ENVIRONMENT

3.1.2.1 Vibration and Acceleration

Vibration environment within the payload bay will not exceed current launch vehicle payload environments.

The maximum steady state acceleration loads in any direction during boost, re-entry, landing and taxiing is 3 g's.

3.1.2.2 Thermal Environment

The shuttle payload bay internal wall temperature limits for preliminary interface considerations are as follows:

Condition	Minimum Temp		Maximum Temp	
Pre-launch	277.6°K	(40°F)	322°K	(120°F)
Launch	277.6°K	(40°F)	338.7°K	(150°F)
On Orbit (Doors-closed)	200°K	(-100°F)	338.7°K	(150°F)
Entry and Post Landing	200°K	(-100°F)	366.5°K	(200°F)

During ascent the Heat Source will rise in temperature from a precooled initial state of less than 644°K (700°F), at a rate of approximately 416°K/hr (750°F/hr). During heatup to operational temperature levels a negligible heat load from the HSA will be dumped to the payload bay walls. Once the HSA reaches the operational temperature level the Mini-Brayton power system should be started up. Waste energy from the Mini-Brayton radiator can be radiated to space by opening the payload doors at this time.

If the payload bay cannot be passively controlled, provisions for limited active thermal control of the payload is available from the shuttle orbiter. Active payload thermal control is supplied by the exchanger in the orbiter to support the payload in the payload bay. The heat transfer capacity for payloads equipment has a peak capacity of 1520 watts (5200 BTU/Hr) during peak orbiter operations.

3.1.2.3 Payload Bay Atmosphere

The orbiter payload bay can be atmospherically controlled while on the launch pad. This provision allows the control of the temperature, humidity, atmospheric composition, and particle contamination of the payload bay by the use of launch site GSE. A nitrogen purge capability is provided for inerting the payload bay prior to launch if required.

The orbiter payload bay is vented during the launch and entry phases, and operates unpressurized during the orbital phase of the mission.

3.1.3 MINI-BRAYTON/SHUTTLE INTEGRATION

1. Mechanical Integration - A transfer module, consisting of carriage type of assembly can provide a safe and convenient method of handling the Mini-Brayton payload and mounting it in the Space Shuttle payload bay. This concept allows the payload to be placed in the transfer module prior to shuttle integration. A key advantage is that ancillary equipment, if required, can be incorporated into the transfer module rather than mounted to the shuttle; for example, the capability to provide coolant gas during ascent or re-entry could be readily accomplished by the transfer module. A disadvantage of this approach is the weight and volume penalty associated with the additional hardware carried into orbit.
2. On-Pad Cooling - On-pad coolant for the HSA Auxiliary Cooling Subsystem will be provided by launch facility ground cooling equipment and ducted by appropriate umbilicals to the HSA in the payload bay. A payload bay service panel will interface with this quick disconnect umbilical and with a short cooling duct in the payload bay that is connected to the ACS inlet port. Upon landing at the end of mission, ground cooling equipment can again provide coolant, as required, during shuttle safing operations.
3. Heat Source Venting - Decay of the PuO_2 fuel generates helium gas which is ultimately vented from the Heat Source. The rate of helium generation at beginning of life is approximately 1.2×10^{-4} scc/sec and is sufficiently small so that the gas can be vented to the payload bay. If for any reason this is undesirable, a vent tube can be provided to dump the helium directly overboard through a payload service panel.

3.2 PRELIMINARY MISSION ANALYSIS

The mission analysis was primarily aimed at identifying the functional operations which occur sequentially starting with fabrication and ending with recovery, including contingencies for aborts and operational options. The mission is depicted in the form of functional flow block diagrams in Figures 3-1, 3-2 and 3-3.

The top level functions (Figure 3-1) corresponding to mission phases are:

8.0 - Fabricate, Assemble, Test and Ship

7.0 - Perform Ground Flow Operations at Launch Facility

6.0 - Perform Prelaunch and Countdown Operations

5.0 - Launch and Inject into Orbit

4.0 - Perform Orbital Payload Checkout

3.0 - Transfer Payload in Orbit

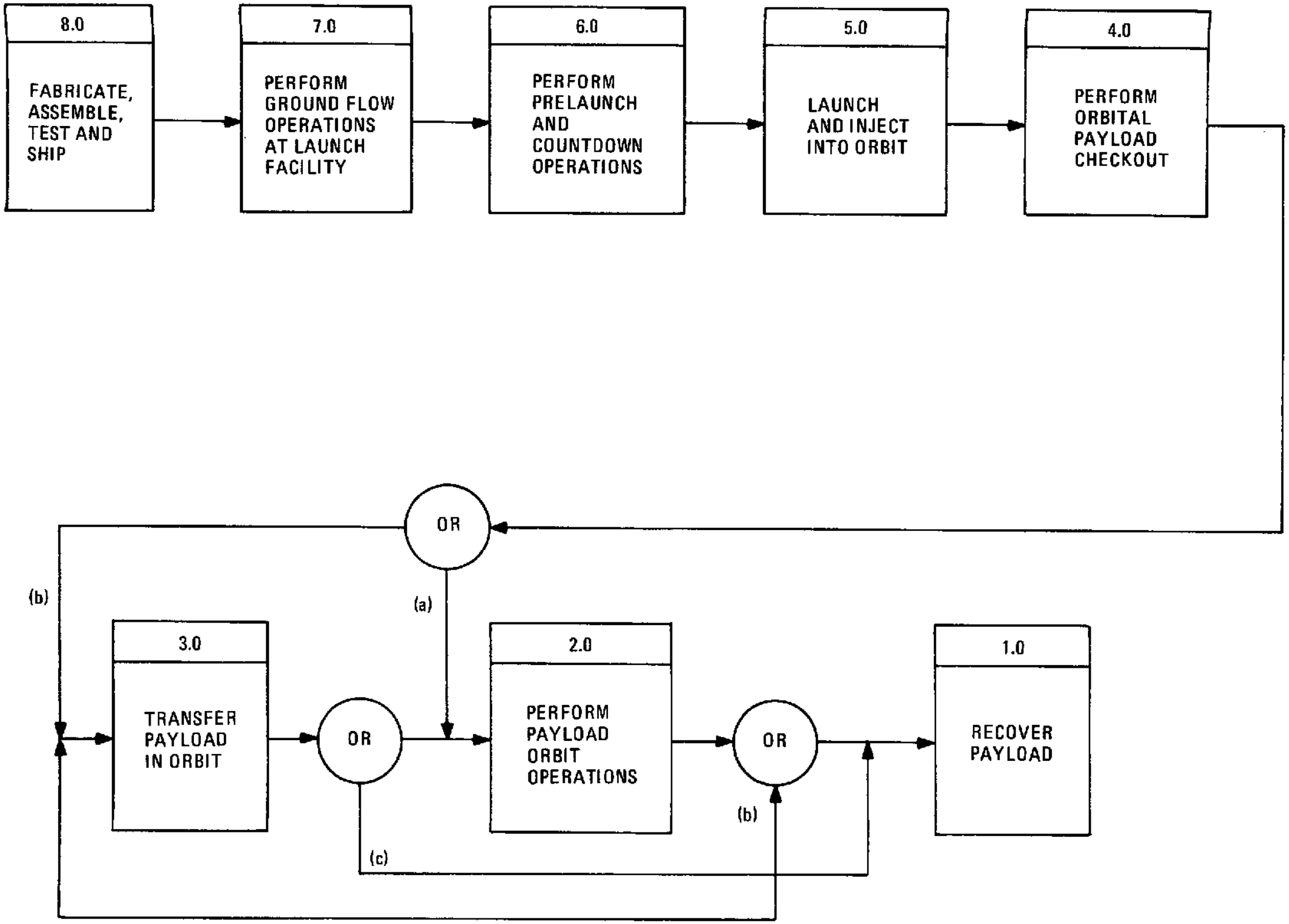
2.0 - Perform Payload Orbit Operations

1.0 - Recover Payload

The option of mission operation of the payload (Mini-Brayton Power Conversion System) in orbit within the shuttle, or on a payload deployed from the shuttle, is shown.

Figure 3-2 shows the first level functional flow from fabrication through shipping to the launch site. It is proposed that the initial Mini-Brayton system tests be performed by the integration contractor with the Electrical Heat Source developed for the MHW-RTG program. After the system is qualified, the Mini-Brayton is acceptance tested at an AEC licensed facility in a system configuration with the isotope heat source. After completion of the tests, the Heat Source is shipped to the launch site separately from other Mini-Brayton hardware in an existing shipping cask designed for the MHW-RTG program. The shipping cask provides cooling of the heat source and requisite radiation shielding.

Figure 3-3 is an integrated functional flow block diagram that shows all the first level functions from launch facility operations through recovery. Options are shown on the functional flow block diagram to either install the Mini-Brayton System (payload) in the Maintenance and Refurbishment Facility, in the Vertical Assembly Building (VAB) either before or after mating of the Solid Rocket Motors (SRM's), or on the pad. Upon landing there is an option of either removing the Heat Source after orbiter safing or



NOTES:

(a) MINI-BRAYTON SYSTEM REMAINS IN SHUTTLE
(b) MINI-BRAYTON SYSTEM DEPLOYED FROM SHUTTLE
(c) SAME LOOP AS (b) BUT OPERATION TAKES PLACE AFTER PAYLOAD IS TRANSFERRED BACK TO SHUTTLE

Figure 3-1. Top Level Functional Flow

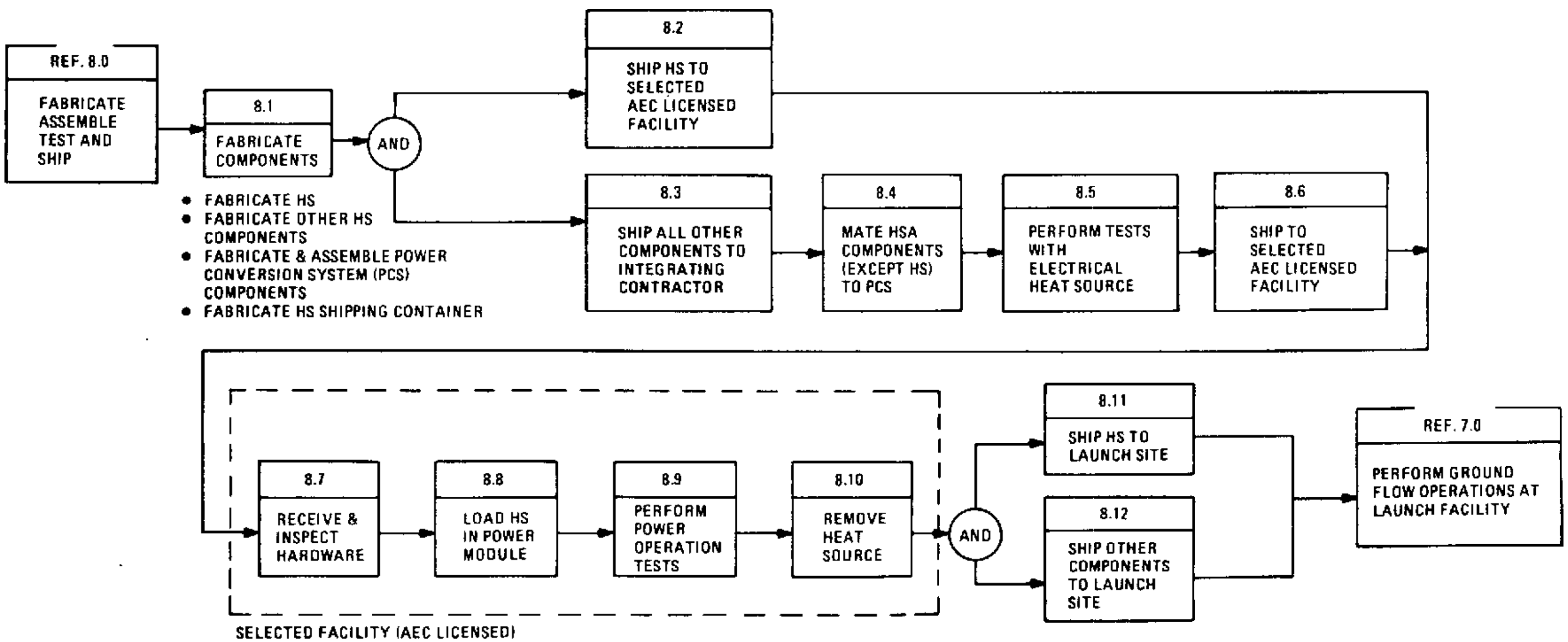


Figure 3-2. Proposed Functional Flow Assembly through Shipping (Flight Unit)

FOLDOUT FRAME 1

FOLDOUT FRAME 2

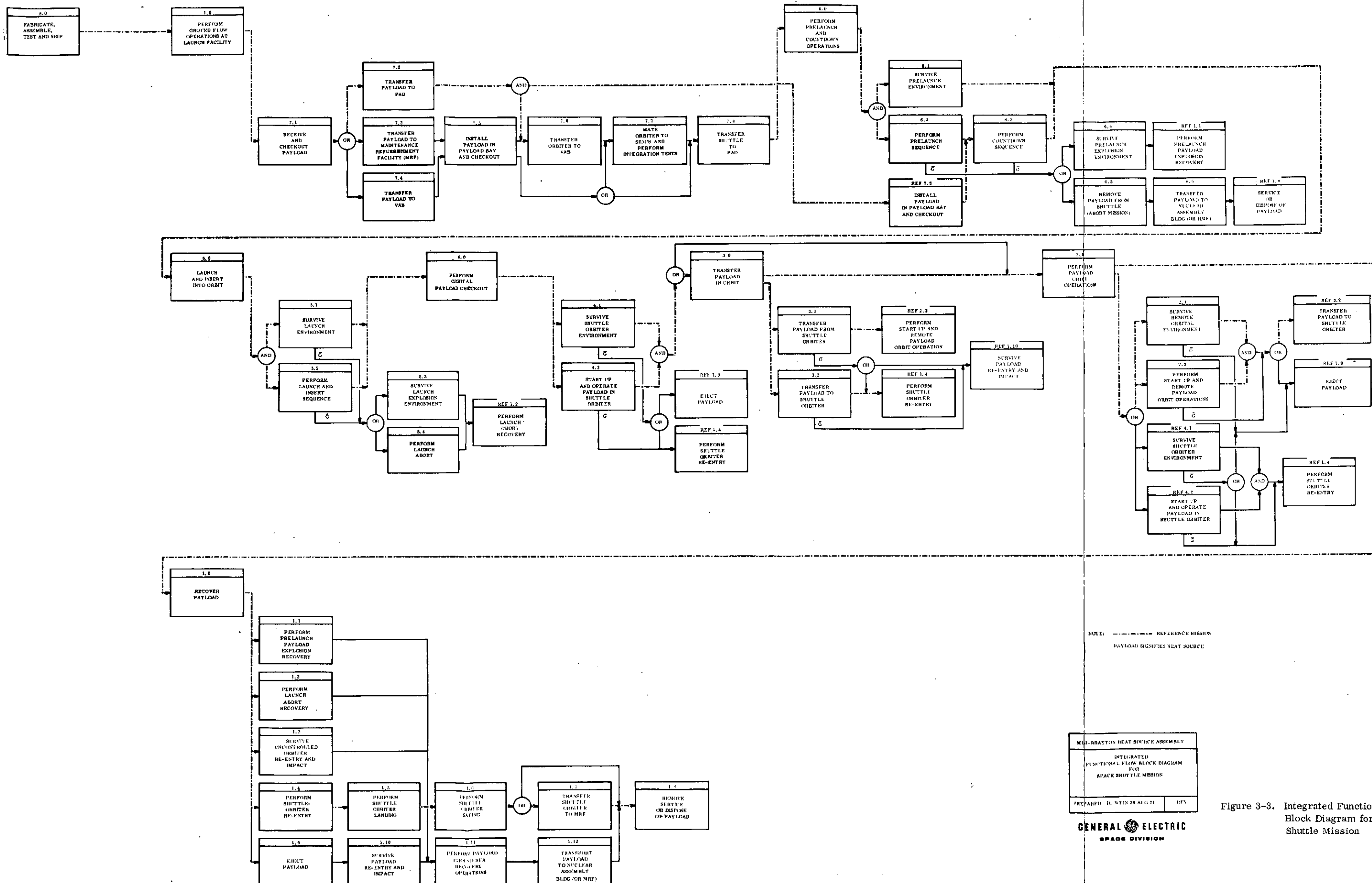


Figure 3-3. Integrated Functional Flow Block Diagram for Space Shuttle Mission

leaving it in the shuttle orbiter and removing it at the Maintenance and Refurbishment Facility. Lines that emanate from the bottom of the functional blocks with a symbol "$\bar{G}$" indicate "NO GO" situations or aborts. The reference mission shown by the dotted lines, however, does not include any aborts.

Briefly this mission is as follows:

Mission Phase	Comments
Ground Flow Operations	The Heat Source is installed in the Shuttle Orbiter payload bay on the pad. Installation and checkout must be accomplished in not more than 10 hours elapsed time prior to T-2 hours.
Prelaunch and Countdown	This period lasts approximately 48 hours and is devoted primarily to verifying the Launch Umbilical Tower/Launch Facility connections, performing final integrated tests servicing the vehicle, loading the crew and passengers and final closeout. It is within this time frame that the Heat Source is installed. Heat Source cooling will be provided by GSE during this phase of the mission. The Mini-Brayton Power Conversion System is not operating during this mission phase.
Launch and Insert Into Orbit	The Mini-Brayton Power Conversion System does not operate during launch and orbit insertion. Provisions are made for monitoring and displaying HSA parameters to the flight crew and mission specialists during this phase and during all ensuing phases when the power system is within the shuttle orbiter payload bay.
Orbital Payload Checkout	During this phase of the mission the Mini-Brayton power conversion system is started up and checked out in the Shuttle Orbiter Payload bay.
Transfer Payload from Shuttle	The Mini-Brayton system is deployed from the shuttle during this phase. It is assumed that the system is attached to a spacecraft which is deployed from the shuttle and is operating during the deployment operation.
Perform Payload Orbit Operations	During this phase the Mini-Brayton System operates on board an earth orbiting spacecraft.

Mission Phase	Comments
Transfer Payload to Shuttle	The Mini-Brayton System is retrieved and transferred back to the Shuttle Orbiter payload bay. Two options are considered, viz: transferring the spacecraft with the Mini-Brayton system attached to it or transferring just the Heat Source back to the Shuttle.
Recover Payload	During this phase the Shuttle Orbiter performs a re-entry and lands at its designated site. Following the landing the orbiter is towed to a safing area where the crew and passengers disembark. It is assumed that GSE will be available to cool the Heat Source at the safing area and during transfer of the Shuttle Orbiter to the Maintenance and Refurbishment Facility where the Heat Source is removed, serviced or disposed of.

SECTION 4

HEAT SOURCE

The Multi-Hundred Watt RTG Heat Source developed for the AEC under contract AT(29-2)-2831 will be used "as is" for the Mini-Brayton design. The first application of the Heat Source will be for the LES 8/9 mission to be launched in 1975. The physical description and specifications are described in the following paragraphs:

4.1 PHYSICAL DESCRIPTION

Figure 4-1 shows a pictorial view of the Heat Source. The primary Heat Source component is the Fuel Sphere Assembly (FSA) which is a self-contained modular fuel element. The FSA's are arranged in six (6) planes of four (4) spheres each; adjacent planes are rotated 45 degrees to achieve nesting and to minimize length. The FSA's are held in place in groups of eight (8) by three (3) segmented graphite retaining rings with conical seats. Woven graphite cloth compliance pads are positioned between each FSA plane to achieve a tight fit without tight tolerance control and to provide vibration damping. Each FSA consists of a sphere of plutonium dioxide 238, having a nominal diameter of 3.7 cm (1.465 inches) contained in a 0.051 cm (0.02 inches) thick iridium shell. The iridium shell, called the Post Impact Containment Shell (PICS), provides the primary fuel containment and together with the fuel is defined as the Post Impact Shell Assembly (PISA). The PISA is protected from impact by a 1.17 cm (0.460 inch) spherical graphite shell, called the Impact Shell. The three basic components, fuel, PICS and Impact Shell, together comprise the FSA.

The 24 FSA's in the retaining rings are surrounded by a 1.02 cm (0.4 inch) cylindrical purified polycrystalline (POCO) graphite ablative heat shield aeroshell, which is designed to provide re-entry protection. Laminated crush-up material is provided at both ends of the cylinder for additional impact protection; threaded graphite and caps complete this part of the assembly.

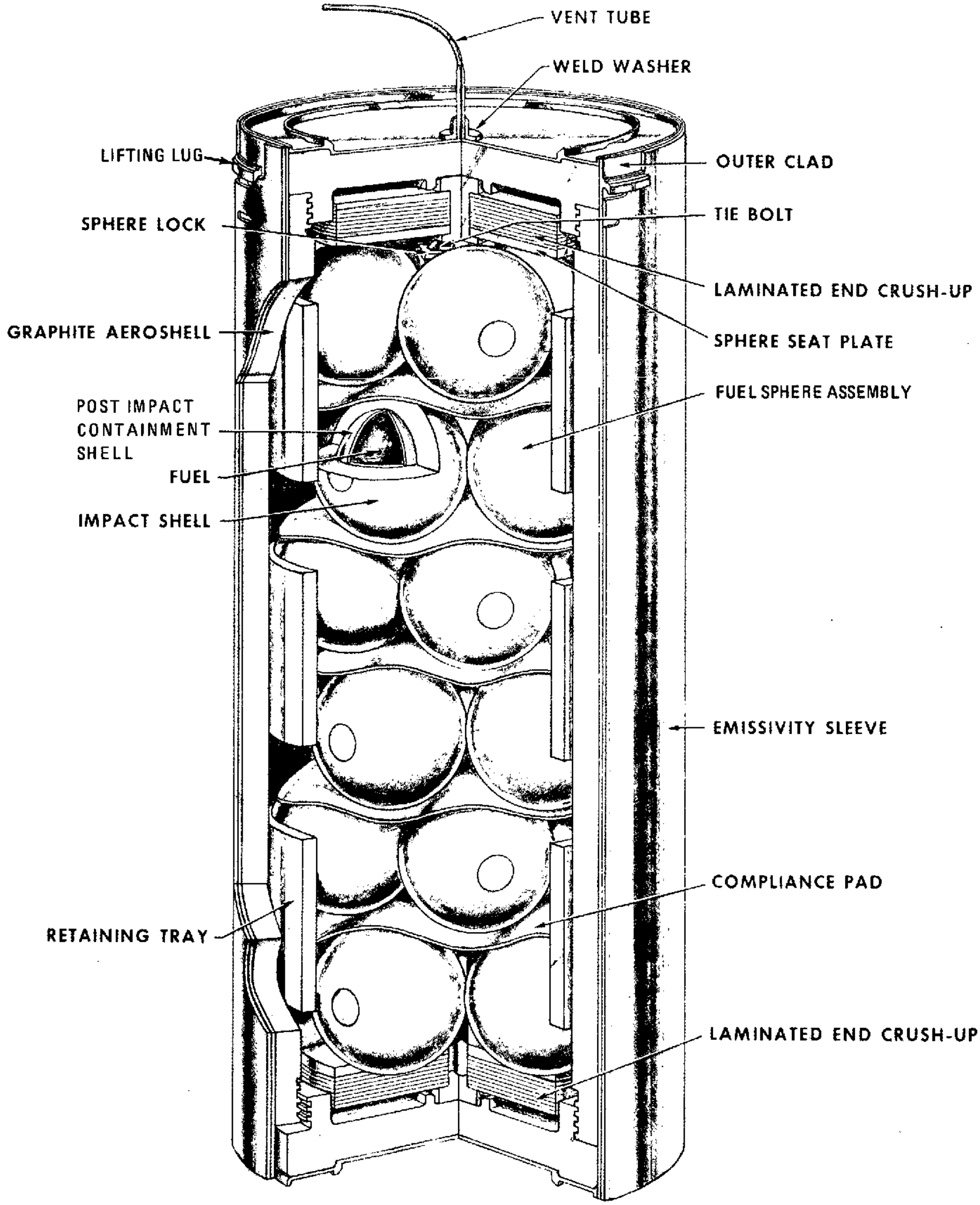


Figure 4-1. MHW Heat Source

The entire assembly is encased with a 0.025 cm (0.010 inch) iridium clad which serves to protect the graphite aeroshell from oxidation during ground handling, to contain the helium generated by isotope decay, and to provide additional re-entry protection for those cases in which multiple skips could be encountered. The iridium clad has three lifting lugs for handling. It is surrounded by a 0.127 cm (0.05 inch) woven graphite yarn emissivity sleeve (also called the "girdle") which slips over the iridium clad and engages three bosses. The emissivity sleeve provides:

1. A high emissivity surface ($\epsilon = 0.85$) to enhance radiation heat exchange,
2. Hoop strength, and
3. Additional re-entry margin.

The heat source has a vent tube protruding from one end of the assembly to vent internally generated helium. The overall maximum envelope of the heat source assembly is:

Length - 42.5 cm (16.69 inches)

Diameter - 18.7 cm (7.347 inches).

The Heat Source weighs approximately 21.6 kg (48 lbs).

4.2 SPECIFICATIONS

The MHW Heat Source is designed to the following specifications:

1. Thermal power - 2400 ± 30 watts.
2. Operating life - 6 years including one year of storage and test (5 years orbital operation)
3. Maximum temperature of any iridium surface - 1773° K (2732° F).
4. Maximum long term steady state operating temperature of external surface - 1373° K (2012° F).

The heat source is designed to immobilize the fuel during potential prelaunch and launch failures. Safety design features are discussed in Section 5.

SECTION 5

SAFETY

The objective of the Safety Study was to specify a set of safety requirements and guidelines for development of a safe Heat Source Assembly design. In order to accomplish this, all potential accident conditions which must be factored into the design to make it safe for handling, storage, launch, operation and recovery have been identified for the baseline mission. The capability of the MHW Heat Source to survive the accident environments has been assessed.

5.1 GENERAL REQUIREMENTS

The general requirements for design of nuclear systems are:

1. Radioactive materials shall be packaged and prepared for shipment in a manner that provides assurance of protection to the public health and safety during transportation of such materials. This will be accomplished by using the approved MHW Heat Source shipping cask and shipping procedures.
2. Radiation protection shall be provided to assure that radiation exposures to personnel and population groups are limited to the lowest possible levels. This will be accomplished by launch operation constraints.
3. Preclude the release and dissemination of radioactive fuel, especially significant respirable particles. This will be accomplished by utilizing the MHW Heat Source which will survive all credible accidents.
4. Maximize long term immobilization of the nuclear heat source following potential accidents. The MHW Heat Source is designed to meet this requirement.

5.2 MHW HEAT SOURCE SAFETY DESIGN CAPABILITY

The MHW Heat Source under development by the AEC and GE has been designed to survive the following environments (Reference 2). The on-pad explosions apply to a Titan IIIC launch. In the absence of detailed definition of shuttle accident environments, the Titan IIIC environments have been used as a point of departure in Section 5.4 for specifying preliminary Mini-Brayton requirements.

5.2.1 EXPLOSION - LIQUID PROPELLANT FIRE

A fireball with temperatures decaying from approximately 2960° K to 1922° K (4900° F to 3000° F) in about eight seconds followed by a residual fire at a temperature of 1297° K (1875° F) lasting for 1/2 hour will not cause release of fuel from a heat source. In the unlikely case that a bare Fuel Sphere Assembly is exposed to the enveloping environment, no fuel release should occur.

5.2.2 EXPLOSION - SOLID PROPELLANT FIRE

A mass of burning propellant with a surface temperature of 2620° K (4250° F) lasting for ten minutes:

1. For the case in which a bare FSA is located on the top of a burning solid fuel segment breach of the fuel containment will not occur. The probability of this condition occurring is extremely remote.
2. For the case in which a Heat Source, an FSA or even a PISA rests between burning propellant segments, no fuel release occurs.

5.2.3 EXPLOSION - BLAST WAVE OVERPRESSURE

Characterization of the blast wave environment on a particular body is dependent on the overall configuration, type of burning propellant and properties of the shock front. Generally a body exposed to direct impingement of a spherically expanding shock wave will receive an instantaneous rise of a reflected shock wave pressure as blast wave impulses on the assembly. The reflected overpressure decays rapidly to the stagnation overpressure in the time it takes to clear the body of reflection effects. The remaining dynamic portion of the blast wave dies out followed by a decay in the static or side on overpressure until ambient levels are reached. The environment experience by a particular body is also configuration dependent and influenced by the degree of attenuation afforded by surrounding or intervening structure. In the case of the MHW-RTG mounted atop the LES 8/9 spacecraft some 3.7 m (12 ft) from a Titan IIIC transtage explosion, the spacecraft offers sufficient attenuation blockage to prevent the reflected shock wave impingement effect. Figure 5-1 shows the predicted environment experienced by the MHW-RTG for a 5% explosion yield.

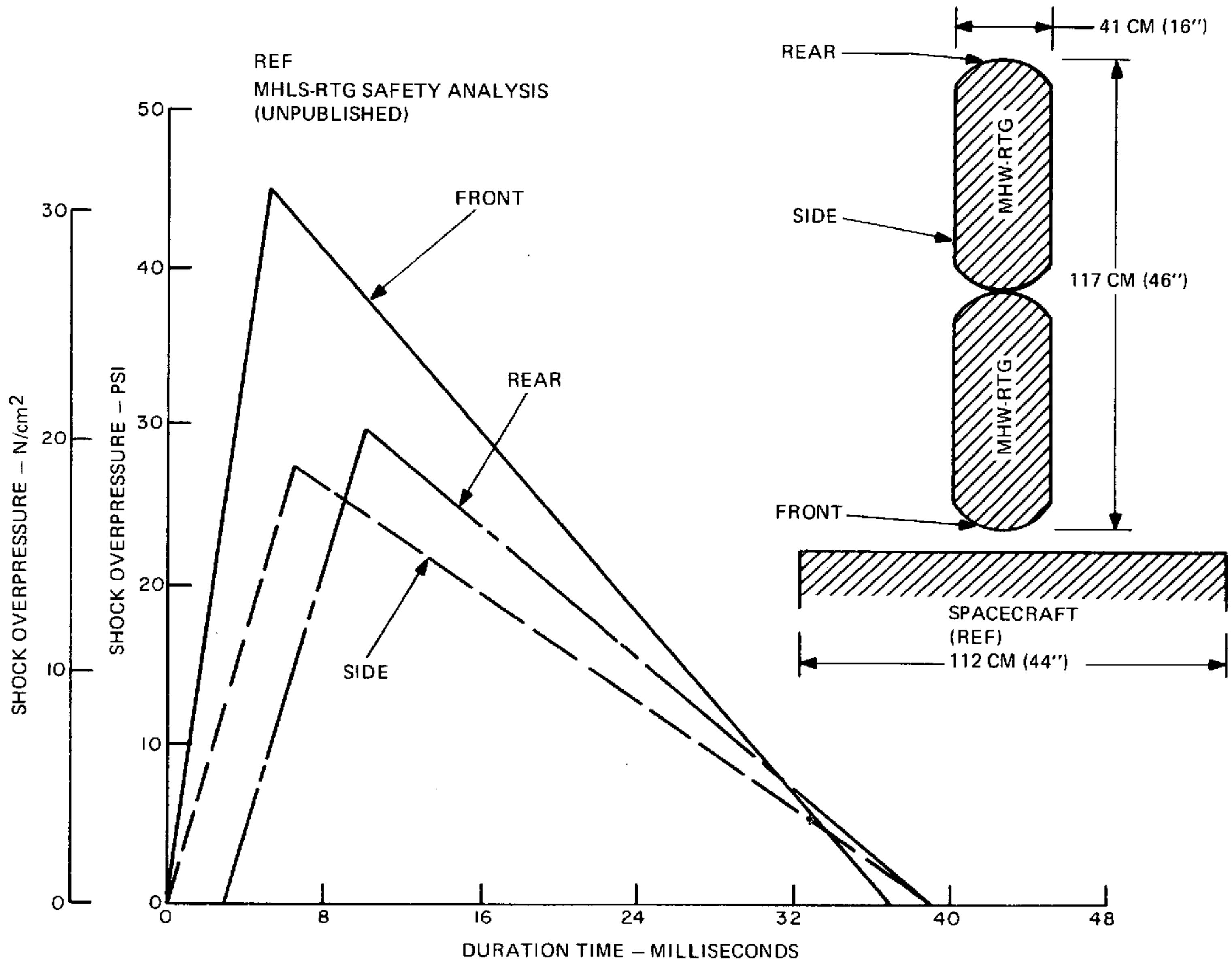


Figure 5-1. MHW-RTG Pressure Loading for an on Pad Explosion

With a Mini-Brayton system arrangement such as that shown in Figure 1-3, structural intervention and attenuation would similarily be afforded to the Heat Source by the Power Conversion System Equipment and Spacecraft Structure. Therefore, the environment shown in Figure 5-1 is typical of what can be expected for a Mini-Brayton System in a similar configuration. Practical considerations of weight does not permit designing the structure for the blast environment; however, for safety reasons assurance must be given that the Isotopic fuel is not released from its encapsulated fuel container. Structural elements will normally breakup at 1% yields, releasing the Heat Source; however the 2 to 4 millisecond typical delay in break up permits attenuation of the primary shock front before arriving at the Heat Source (HS). Principle damage to the HS from blast wave is expected from impacting of structural fragments and components located in the near vicinity of the HS such as those housed within the Power Conversion Systems (PCS). Analysis of the MHW shows the HS will survive a freefall drop from a pad abort of 42.5 m/sec (140 ft/sec) after being exposed to minor damage impacts from equipment at velocities of 21.3 to 48.5 m/sec (70 to 160 ft/sec) with respective masses of 17.2 and 7.7 kg (38 and 17 lb). The largest mass equipment items in the PCS consists of the Rotating unit, ~8.2 kg (~18 lbs) and the Recuperator, ~15.8 kg (~35 lbs). As such, it is concluded that no damage of the Mini-Brayton HS, as a result of an environment equivalent to a Titan IIIC 5% yield blast environment, will occur which will cause release of the fuel from its Post Impact Containment Shell (PICS) when configured in an arrangement similar to that shown in Figure 1-3.

5.2.4 RE-ENTRY

The Heat Source is designed to survive re-entry from orbital altitudes with initial conditions of 121,920 km (400,000 feet) and velocities of up to 11,064 m/sec (36,300 ft/sec) and path angles of 0 to 90 degrees to the local horizontal. The spectrum of reentry conditions includes the following:

1. Minimum reentry angle - the angle separating multiple skip and capture reentries. This is the most severe thermal response situation and a severe ablation case. Analysis indicates a 53% margin of ablative material.

2. Multiple skip - this is the most severe ablation case. Analysis indicates a 27% margin of ablative material.

3. Steep angle - this is the most severe thermal stress condition. Analysis indicates a design margin of 28% in the tensile stress at the inner aeroshell layers at the stagnation point. Compressive stress cases have margins greater than a factor of 3-1/2.

5.2.5 IMPACT

The MHW has successfully demonstrated the survival capability of the Heat Source Fuel Sphere Assemblies (FSA's) at HS impact velocities up to 87 m/sec (286 ft/sec) on a hard granite surface. Single sphere FSA tests have demonstrated 89 m/sec (295 ft/sec) and rocket sled impact tests of an assembled HS has demonstrated 286 ft/sec. Expected terminal velocities for the normal reentry conditions defined above are 78 m/sec (256 ft/sec), thus giving approximately a 10% margin.

Figure 5-2 presents an analytical summary of the HS impact velocities required in order to release fuel from the Post Impact Containment Shell (PICS) when the HS is impacted on various earth media.

5.3 MINI-BRAYTON RADIATION SHIELDING REQUIREMENTS

5.3.1 PERMISSIBLE DOSE LEVELS

The allowable exposure limit currently in use by NASA (References 3 and 4) is a yearly average of 200 mrem/day to bone marrow (5 cm depth) from all radiation sources. Cosmic, galactic, and trapped radiation contribute approximately 50 mrem/day. Therefore, the shuttle crew exposure should by limited to a maximum allowable dose rate from the nuclear payload of 150 mrem/day, or 6.25 mrem/hr. The 150 mrem/day maximum allowable dose is based on yearly averages. Since most crew time durations are short, higher dose rates may be permissible for shorter periods of time.

5.3.2 HEAT SOURCE NUCLEAR RADIATION ENVIRONMENT

The total dose rates from one, two and three MHW Pu-238 Heat Sources as a function of distance from the fuel is given in Figure 5-3. The doses are shown for neutron

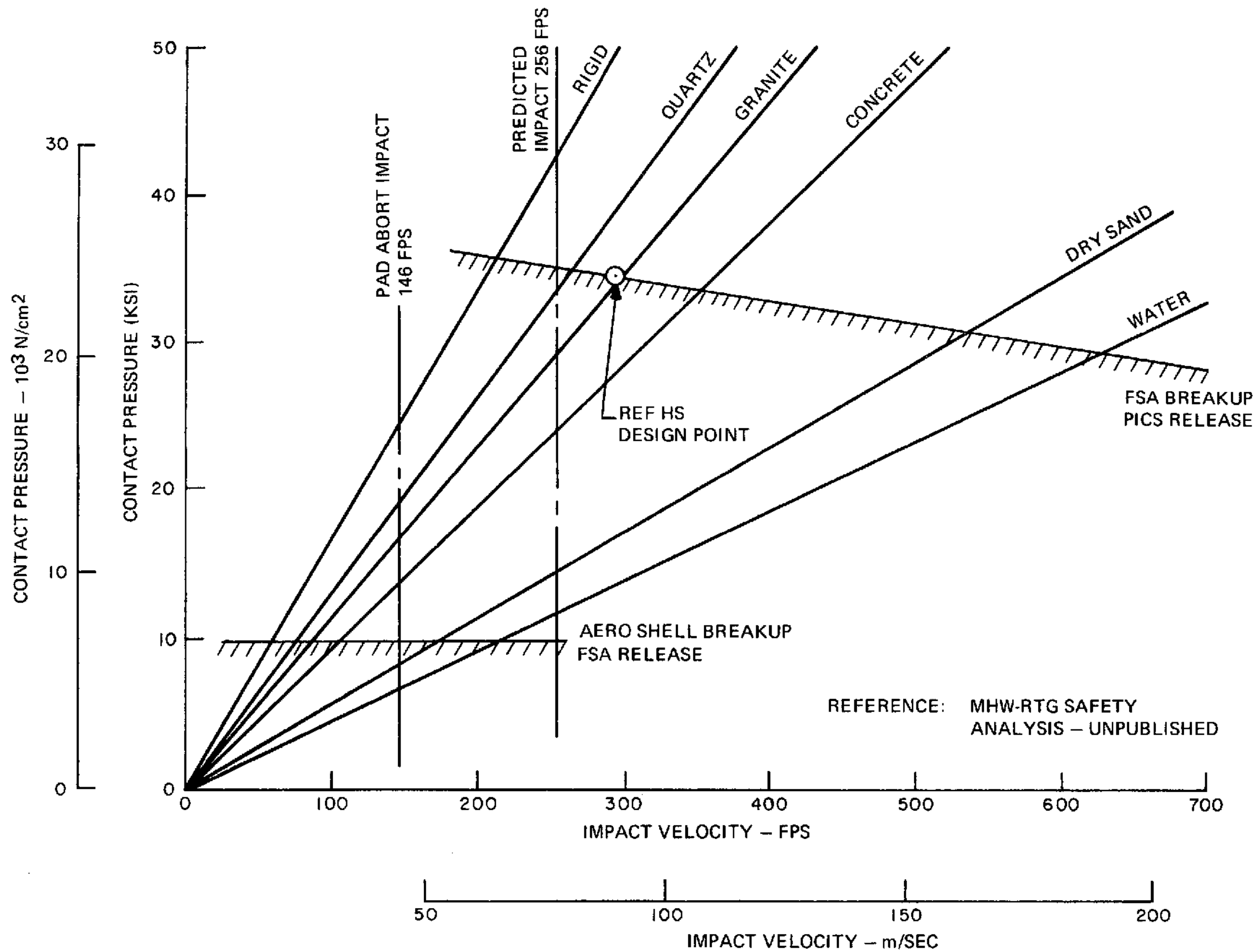


Figure 5-2. Heat Source Ground Impact Side-on

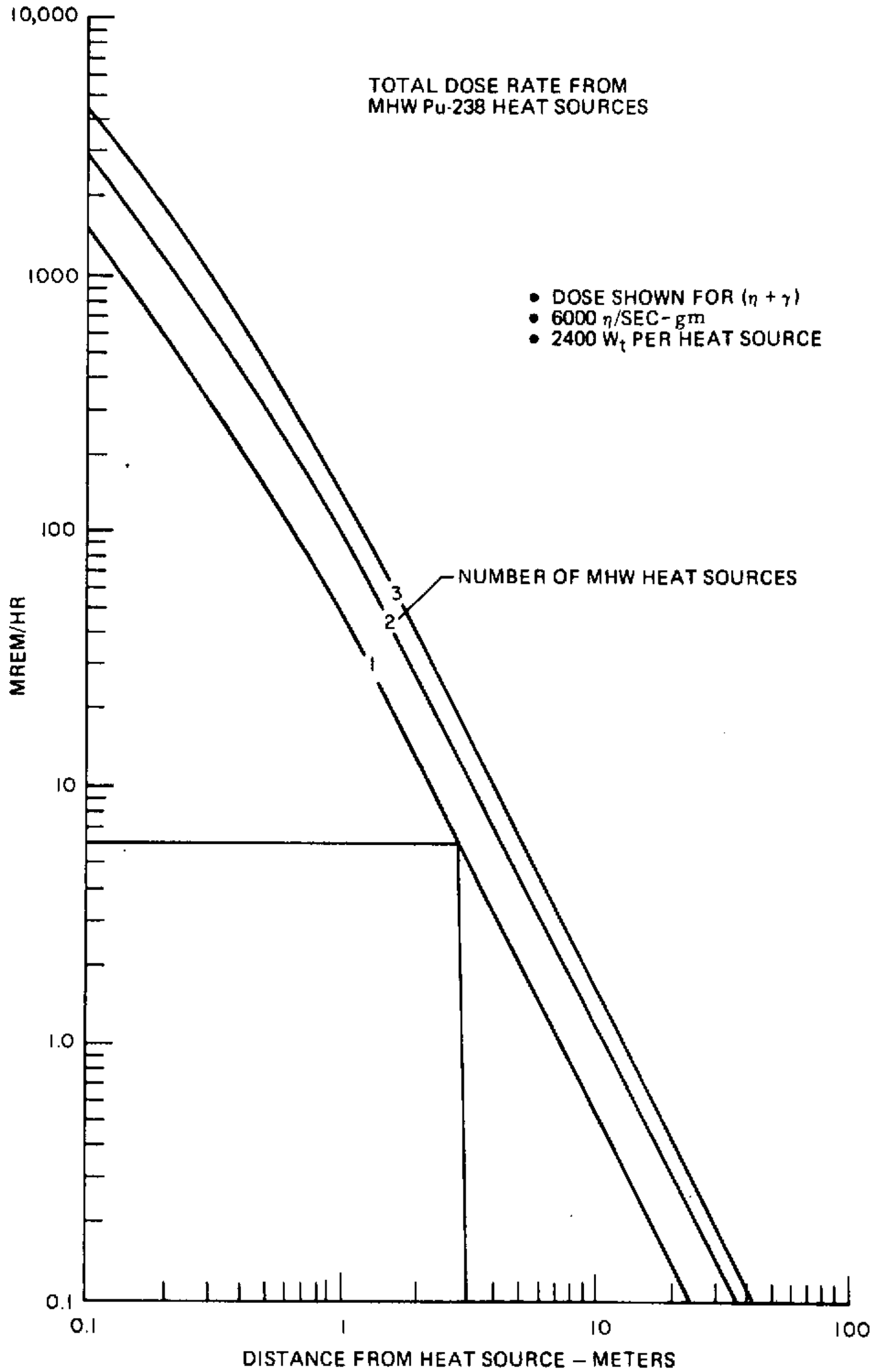


Figure 5-3. Total Dose Rate from MHW Pu-238 Heat Sources

and gamma radiation. The neutron source strength was taken as 6×10^3 Neutrons/sec - gm Pu (Reference 5). The total mass of PuO_2 in a single 2400 watt heat source is 6000 gms.

Figure 5-4 shows the number of hours per day which a shuttle crew member can spend in the vicinity of the HSA's. It is evident that if the HSA's are located approximately 5.0 meters from the crew, then the largest Mini-Brayton System (3 HSA's) need not be shielded to protect the crew compartment. It is also evident that reasonable amounts of time may be spent by a crew member in close proximity to the HSA's for normal work in the shuttle bay. It is concluded that radiation shielding will not be required to protect personnel in the shuttle.

5.4 POTENTIAL MISSION ACCIDENTS

Accidents and aborts which have a potential effect on nuclear safety may be encountered in any of the mission phases. Some of the resultant accident environments follow directly after or represent the immediate result at the time of an accident or abort, such as the blast wave and the liquid propellant fireball or solid propellant fire resulting from a shuttle catastrophic failure. Most of the remaining accident environments will be experienced by the HSA or Heat Source at times considerably later than the initiating event and will be directly influenced by the HSA or Heat Source design; these include the unplanned re-entry of the HSA or Heat Source as a result of a mission abort after launch or a decay from an operational orbit. Other accident environments may occur as a result of an operational failure of the Mini-Brayton Power Conversion System itself, such as loss of gas loop integrity resulting in a Heat Source overtemperature condition. These potential mission accidents are summarized in Figure 5-5 and are discussed below.

5.4.1 GROUND HANDLING ACCIDENTS

Ground handling includes all operations involving the Heat Source up to the time at which it is installed in the shuttle. Included are ground transportation, storage, and assembly of the Heat Source into the HSA. Postulated accidents are as follows:

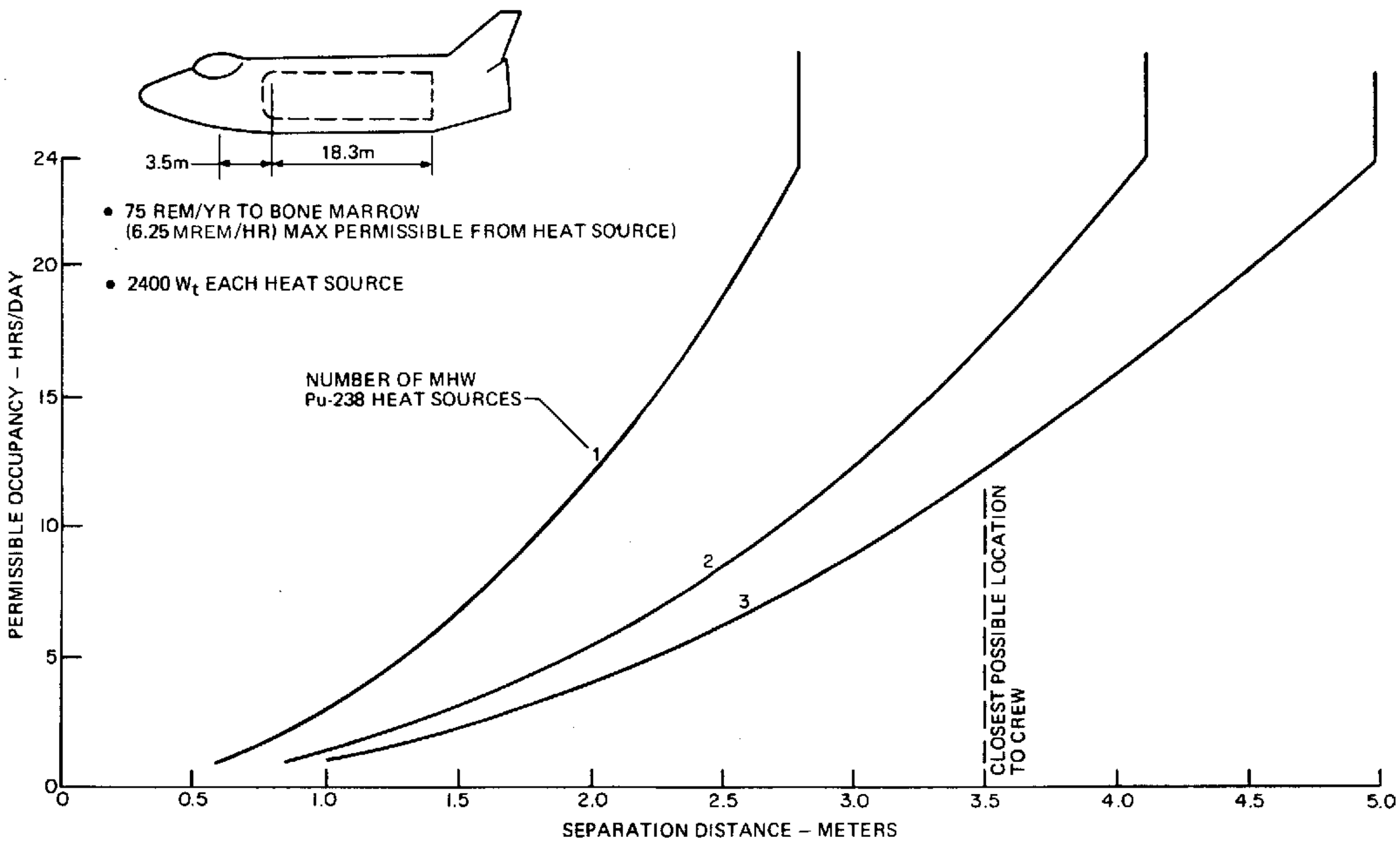


Figure 5-4. Radiation Exposure Limits for Mini-Brayton Power System

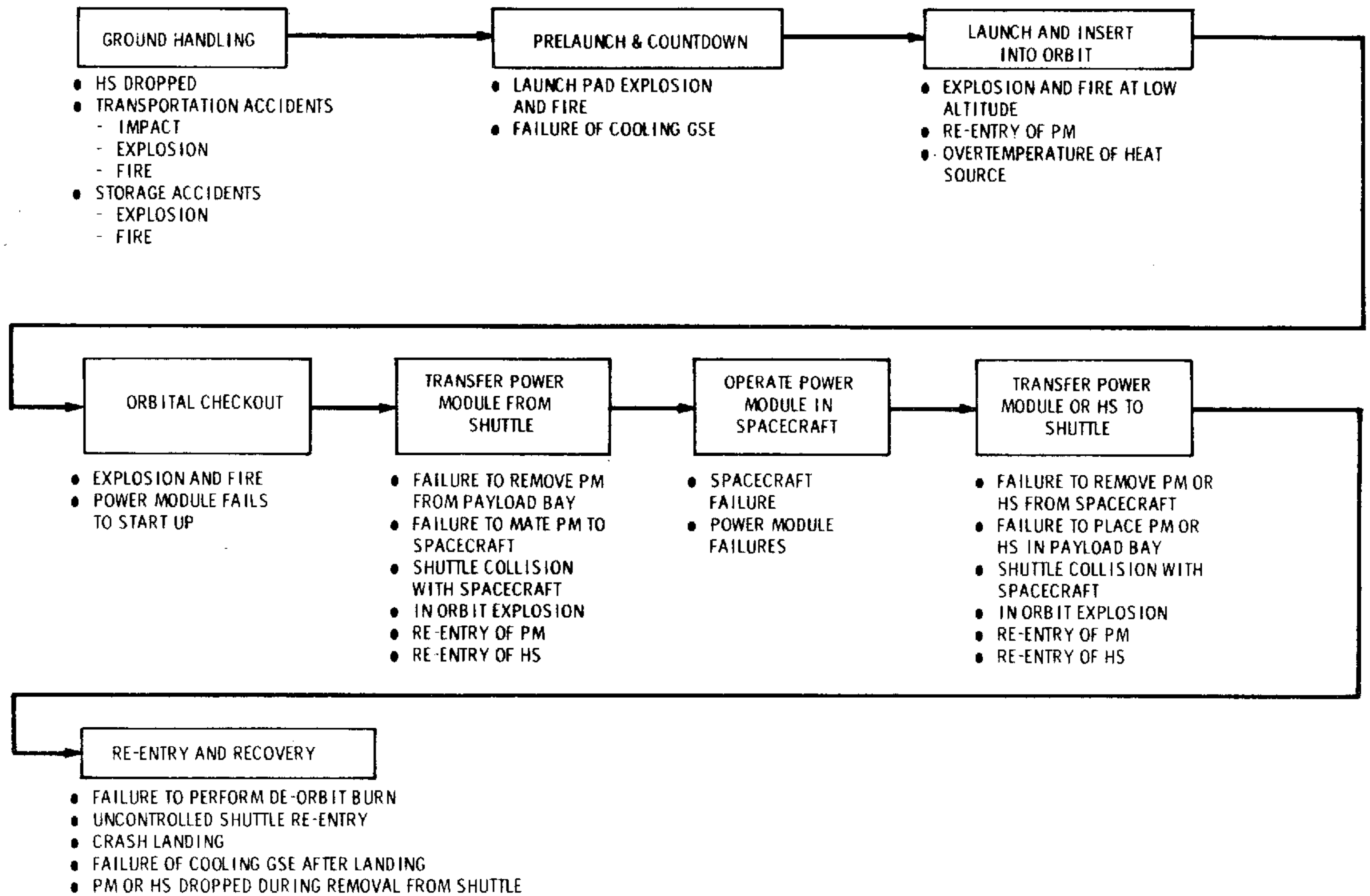


Figure 5-5. Potential Mission Accidents

1. HSA Assembly Accident — During the assembly operations, the Heat Source may be dropped while it is being installed in the HSA. Because of the present design characteristics of the MHW Heat Source, no radiological hazard is considered credible.

2. Transportation Accidents — Because of the present design characteristics of the MHW Heat Source no radiological hazard arising from transportation accidents is considered credible.

3. Storage Accidents — Various accidents (natural disasters, fire, etc.) are possible during the storage periods both before arrival at and while at the launch site. During these periods the Heat Source is contained in its shipping cask. Because of the protection afforded by the shipping cask, and the fact that the environments are less extreme than those to which the Heat Source will survive, no radiological hazard is considered likely.

4. Heat Source or HSA Dropped During Installation on Spacecraft — Because of a mechanical failure or human error, the Heat Source or HSA may be dropped while it is being installed on the spacecraft. Because of the low drop heights involved with this type accident, no radiological hazard is identified.

The accident environments identified during these phases of the mission prior to prelaunch are less severe than the MHW design criteria, hence there are no radiological hazards and no impact on the Mini-Brayton HSA design.

5.4.2 PRELAUNCH AND COUNTDOWN ACCIDENTS

Prelaunch and countdown covers the period from installation of the Heat Source on the pad to boost ignition.

Accidents in this phase can be initiated during fueling, checkout, countdown and ignition operations. Non-catastrophic accidents are ignored because the Heat Source can be retrieved intact. Catastrophic failures result in an explosion followed by liquid and/or solid propellant fires. The explosion subjects the HSA to a shock overpressure and impulse environment. A fire subsequent to the explosion is also possible. A liquid propellant fire can subject the HSA to a fireball environment. Subsequent collapse of the shuttle vehicle and/or release of the HSA can immerse the HSA in a liquid propellant afterfire or a solid propellant fire.

The environments resulting from accidents in this phase are:

1. Explosion
2. Liquid propellant fire
3. Solid propellant fire
4. Impact
5. Fragmentation

The explosion (blast overpressure), fire and fragmentation environments are not yet well defined for the shuttle. Estimates, however, have been made for these potential accident environments based on other launch vehicles. It is likely that following an explosion on the launch pad the HSA or Heat Source will be separated from the Shuttle and will fall on the concrete launch pad or soil surrounding the pad. These impacts will be relatively low velocity impacts - considerably less than reentry terminal velocities for which the Heat Source is designed to survive. The HSA or Heat Source can also possibly fall in pools of deluge water which collect on the launch pad as a result of the large volume of water sprayed onto the pad and tower for fire control. The potential radiological hazard, if any, is being evaluated on the Multi-Hundred Watt RTG Program and will be assessed for impact on Mini-Brayton safety requirements.

5.4.2.1 Explosion Blast Overpressure

The estimated static and reflective overpressure fields as a function of distance and explosive yields (equivalent percent of TNT) are given in Figures 5-6 and 5-7. The estimated reflected impulse is shown in Figure 5-8. The curves given for 32% yield are considered to be applicable to a Shuttle explosion. A preliminary evaluation of the MHW Heat Source design indicates that it is probable that it will survive the overpressure environment without release of fuel. Further analysis of the Heat Source capability as well as the overpressure environment however is required to be definitive on the probability that the nuclear fuel will be contained in the higher blast overpressure that is anticipated for the Shuttle.

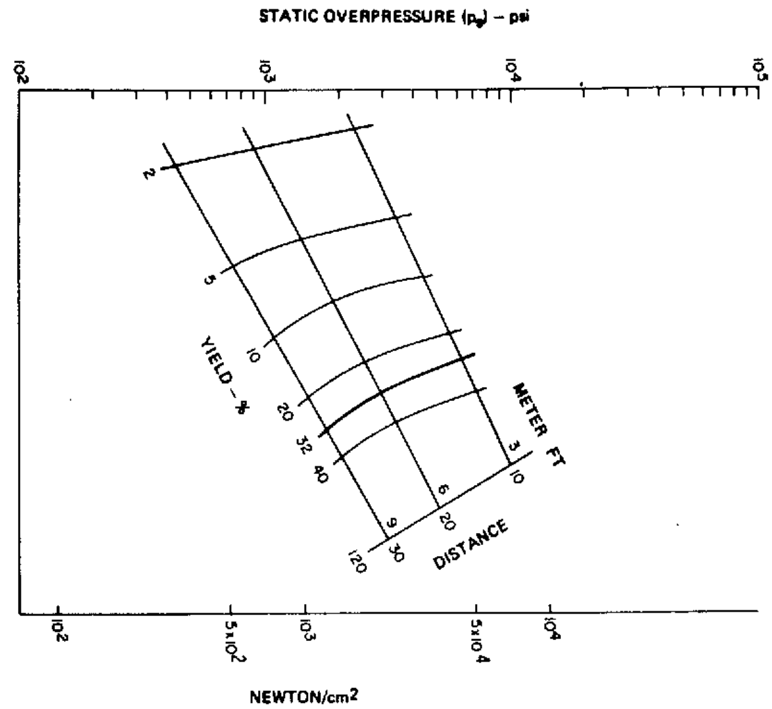


Figure 5-6. Shuttle Blast Static Overpressure

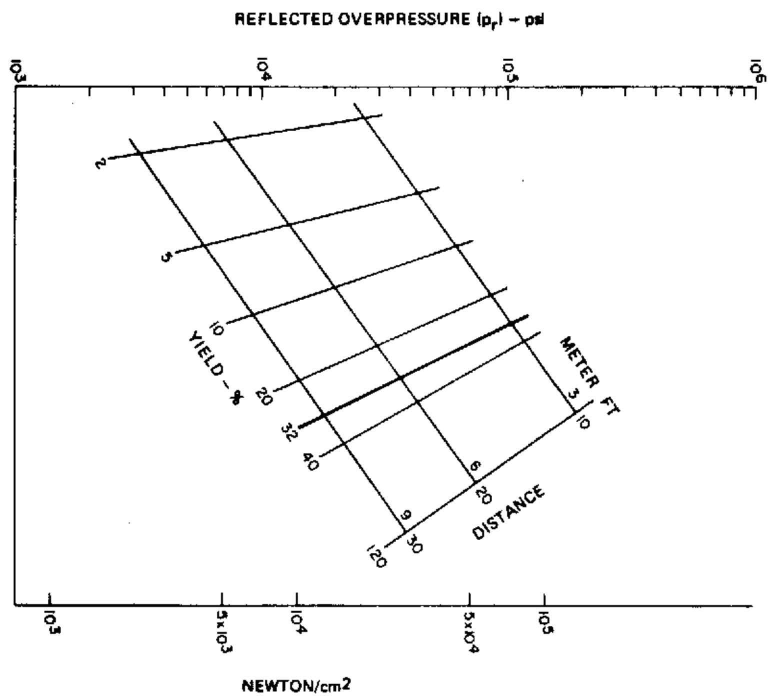


Figure 5-7. Shuttle Blast Reflected Overpressure

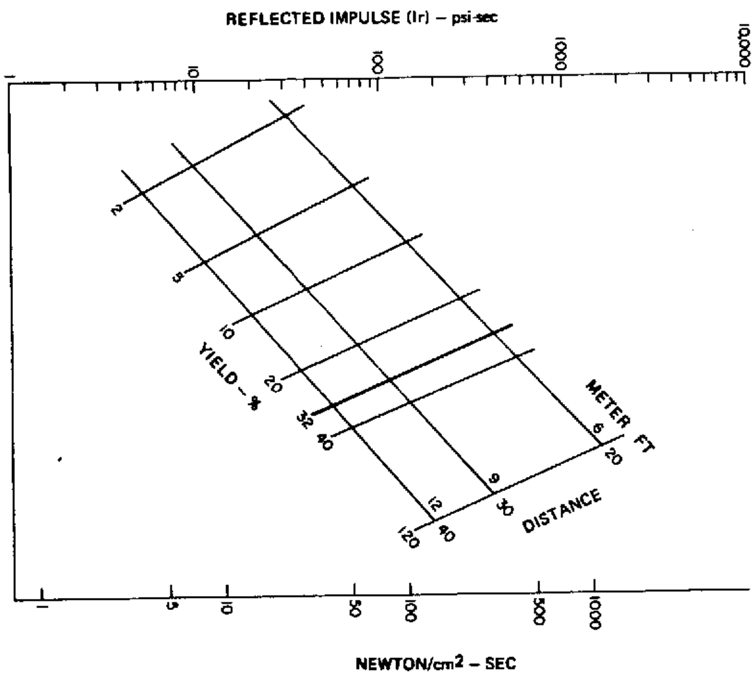


Figure 5-8. Shuttle Blast Reflected Impulse

5.4.2.2 Explosion - Fire

Fire environments resulting from an on-pad accident may result in ignition of the liquid and/or solid propellants in the shuttle. A liquid propellant fire is characterized by a fireball which can envelop the shuttle; the estimated temperature (see Figure 5-9) falls off rapidly from ~3000° K (4940° F) as the fireball dissipates in about 14 seconds, and remains essentially constant at 1297° K (1875° F) during the 30 minute afterfire. Also shown on Figure 5-9 for comparison is the Titan IIIC fireball temperature profile. Here the fireball dissipates in about 7.5 seconds.

A solid propellant fire is characterized by burning of segments of the solid fuel. Temperatures are estimated to remain constant at approximately 2600° K (4220° F) for about 10 minutes.

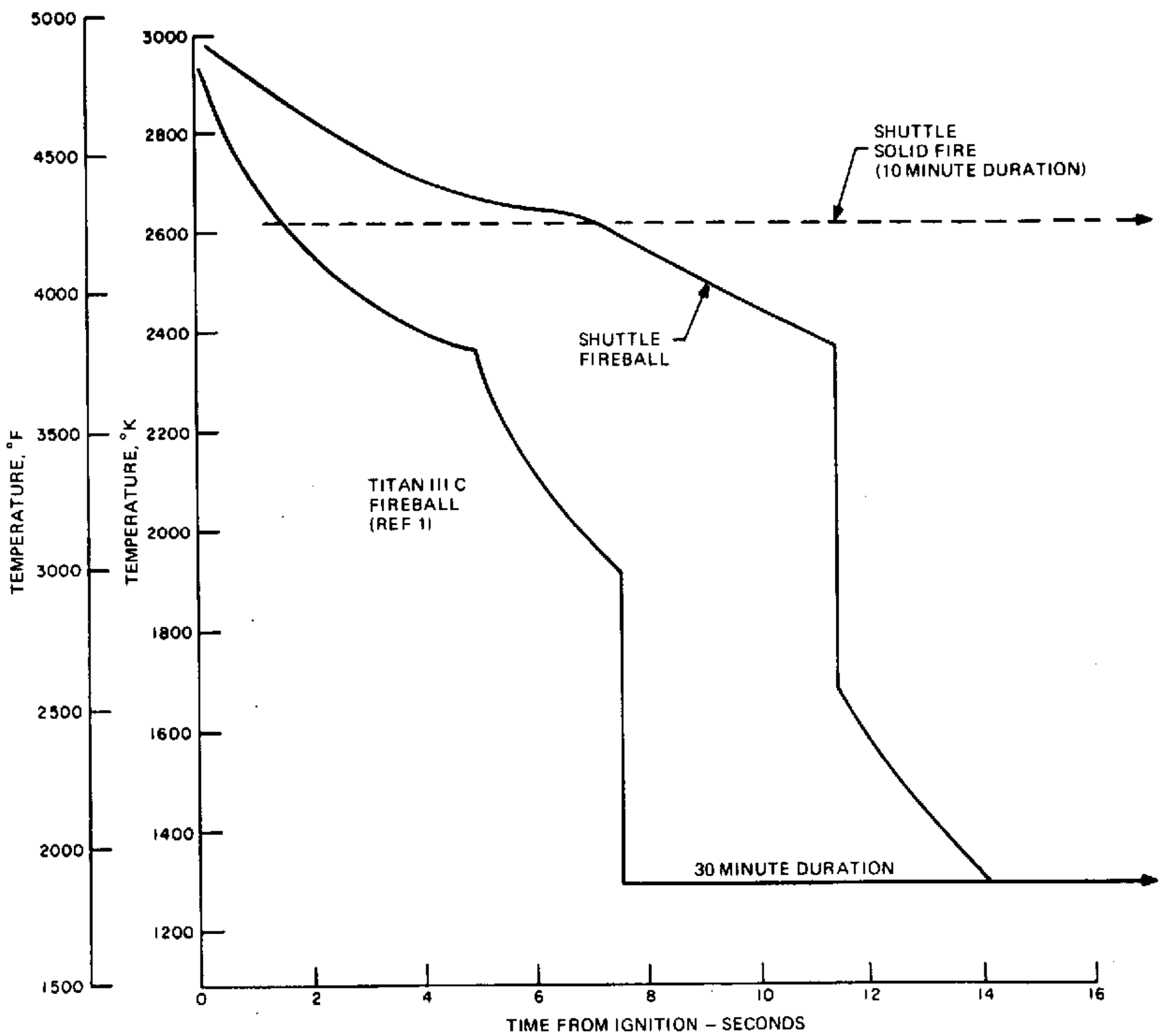


Figure 5-9. Estimated Shuttle Explosion Thermal Environment

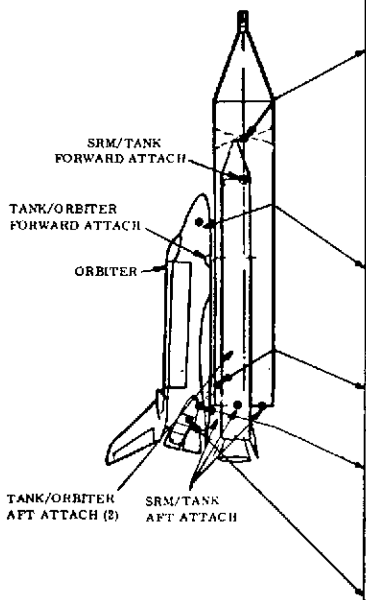
If a free intact Heat Source or Heat Source Assembly is exposed to the high temperature Titan IIIC environment or is in contact with burning solid propellant segments, no radiological hazard will occur as discussed in Paragraph 5.2. It has also been determined that if an individual FSA falls and remains on a segment of burning solid fuel, breach of the fuel containment will not occur. No breach will occur if the FSA is between burning solid propellant pieces. It has also been determined analytically (Reference 2) that no release of isotope fuel will occur if an FSA is enveloped in a Titan IIIC liquid fireball. No analysis has yet been made to determine the effect of the longer lasting fireball postulated for the shuttle on the survivability of the HSA, Heat Source or FSA's when exposed directly to the fireball. It is considered however, that the thermal inertia of these components will sufficiently attenuate the effect of the larger integrated fireball flux.

5.4.2.3 Explosion - Fragmentation

High velocity fragments resulting from a shuttle explosion presents a potential hazard to the isotope Heat Source. Fragmentation can originate from propellant tanks in both forward and aft regions of the shuttle and can breach an unprotected HSA and Heat Source.

Table 5-1 summarizes these shuttle explosion centers and the estimated fragmentation environment. The orbiter configuration and propellant quantities were obtained from Reference 6. Five explosion centers are identified, viz, the external boost liquid fuel tanks between the LO_2 and LH_2 bulkheads, the orbit reaction control hydrazine tanks in the forward section of the orbiter, the LO_2 and LH_2 line connections from the external tanks to the orbiter main engines at the rear of the orbiter, the left and right rear external hydrazine orbit reaction control system orbiter tanks, and the left and right external pod orbit maneuvering orbiter fuel tank. Both primary and secondary fragmentation sources are estimated, the secondary sources being defined as those fragments that result from secondary effects of the explosion, eg., release of fasteners due to failure of structure or due to collision with primary fragments from the explosion center.

TABLE 5-1. POSSIBLE EXPLOSION SOURCES AND ESTIMATED EFFECTS



	Explosion Center	Propellant Amount	Yield	Overpressures		Fragmentation Source		Fragment Velocities		Inherent Fragment Protection for Fuel Containers	
				Static	Reflected	Primary	Secondary	Primary	Secondary	Primary Fragments	Secondary Fragments
#1 EXTERNAL TANK BETWEEN LO_2 AND LH_2 BULKHEAD	#1	1,1715,000# LH_2 LO_2	32%	5000 psi @ 20' Est. Note: These values are approximately 2 times those in 22 Sept. 72 design review	80,000 psi @20' Est.	• 2024 connecting skirt between LO_2 and LH_2 tanks • Estimated 20' of 2219 either side of explosion center • 2219 tanks are welded construction. Milled skins, machined rings • 2024 skirt assembled with mech. fastners Milled skins, formed and machined rings	Crushed orbiting vehicle - high deflection and fracturing of rings, frames, supports, wing carry thru, longerons, etc. • Release of high strength fastners • Possible scissors effect	<5000'/sec @ 10 Est.	Estimated <1500'/sec for fractured steel/alum/titanium fastners. <2000'/sec	Excellent Difficult path into cargo area for fragments from explosion area, particularly in area of wing carry thru structure, main support even though structure is crushed.	Poor Crushing of major rings - inner chords in tension breaking and releasing hi strength fastners inward - relatively small size hi velocity, dense fastners - no inherent protection except Poco shell, heat exchanger, and Mini-Brayton radiator.
#2 ORBIT RCS	#2	Hydrazine 3000# Est.	2% to 5% Est.	Low	Low	• Tanks and fittings • Adjacent bulkhead • Nose structure and skin	Local crushing of shell aft of bulkhead (hydrazine explosion could institute other explosion)	Estimated <2000'/sec	Estimated <500'/sec	Excellent Several bulkheads equipment, etc. in path to cargo compartment.	Excellent
#3 LH_2, LO_2 SUPPLY TO ORBITER	#3	LH_2 and LO_2 Leakage or line rupture		Low	Low	• Bulkhead structure (end bulkhead of cargo compartment)	Negligible (could institute other explosions)	Estimated <2000'/sec	Negligible	Fair Single bulkhead separates explosion center from cargo compartment.	Poor But secondary fragments negligible unless other explo. in aft sect. initiated.
#4 ORBIT RCS	#4	Hydrazine 3600# total (1800#/side) Est.	2% to 5% Est.	Low	Low	• Pod structure tanks and fittings possibly end bulkhead to cargo compartment	Release of fastners from end bulkhead (could institute other explosions)	Estimated <2000'/sec	<500'/sec Estimated	Fair Single bulkhead separates explosion center from cargo compartment.	Poor No protection except as in 1.
#5 ORBIT MANEUVERING	#5	Nitrogen Tetroxide Monomethyl-Hydrazine 24,400# total (12,000#/side)	2% to 5% Est.	Low	<40 psi at 20' range (estimated)	• Pod structure tanks, fittings possibly end bulkhead to cargo compartment	Local crushing of shell. Possible release of fastners (could institute other explosions)	Estimated < 3000/sec at source	<1500'/sec Estimated	Fair Single bulkhead separates explosion center from cargo compartment.	Poor No protection except as in 1.

5.4.2.3.1 Explosion Center - 1 External Boost Tank — Origins of fragments from this explosion center are depicted in Figure 5-10 and are as follows:

1. High velocity fragments - near radial trajectory from 2024 cylindrical skirt section connecting LO_2 and LH_2 tanks.
2. Fragments from LH_2 dome - lower velocity (estimated 920 m/sec (3000 ft/sec) range).
3. Fragments from LH_2 tank section - 6 meters (20 ft) below joint - estimated velocity range 460 m/sec (1500 ft/sec).
4. Fragments from the remainder of tank resulting from massive tearing, peeling and collapse under the explosion pressurized head of fuel and external static/reflected pressures from the explosion.

The effect of these particles on the orbiter are listed below:

1. Primary Fragmentation from External Tank and Skirt Section - In time for fragments to travel beyond the payload compartment (0.05 sec range), the orbiter remains close to external tank. Those particles traveling into the orbiter payload compartment path are expected to be at relatively low velocity, 460 m/sec (1500 ft/sec). The path for primary fragmentation into the payload compartment is blocked by floor frames, floor wing carry through structures, bulkheads, landing gear support structure, etc.
2. Secondary Fragmentation
   a. Direct impact of fragments on fasteners and fittings of the orbiter structure may release secondary fragments which will travel at lower velocities.
   b. Massive collapse of the orbiter structure caused by static and reflected overpressures may release fasteners.

   Expected fragments are steel/titanium/aluminum fasteners up to 0.95 cm dia x 2.54 cm (0.375 dia x 1 inch) long with velocities up to 460 m/sec (1500 ft/sec).

   If one assumes 500 fragments as an expectation of the number of primary particles originating from the explosion center, and that these are distributed uniformly in a sphere, then only about four particles will impact the 6.1 m (20 ft) front bulkhead of the orbiter which is located 18.3 m (60 ft) from the explosion center. The majority of these, if not all, should be stopped or the velocity greatly reduced, by the nose section. It must be assumed, however, that some deflected fragments such as released fasteners will enter the payload bay at velocities up to 610 m/sec (2000 ft/sec).

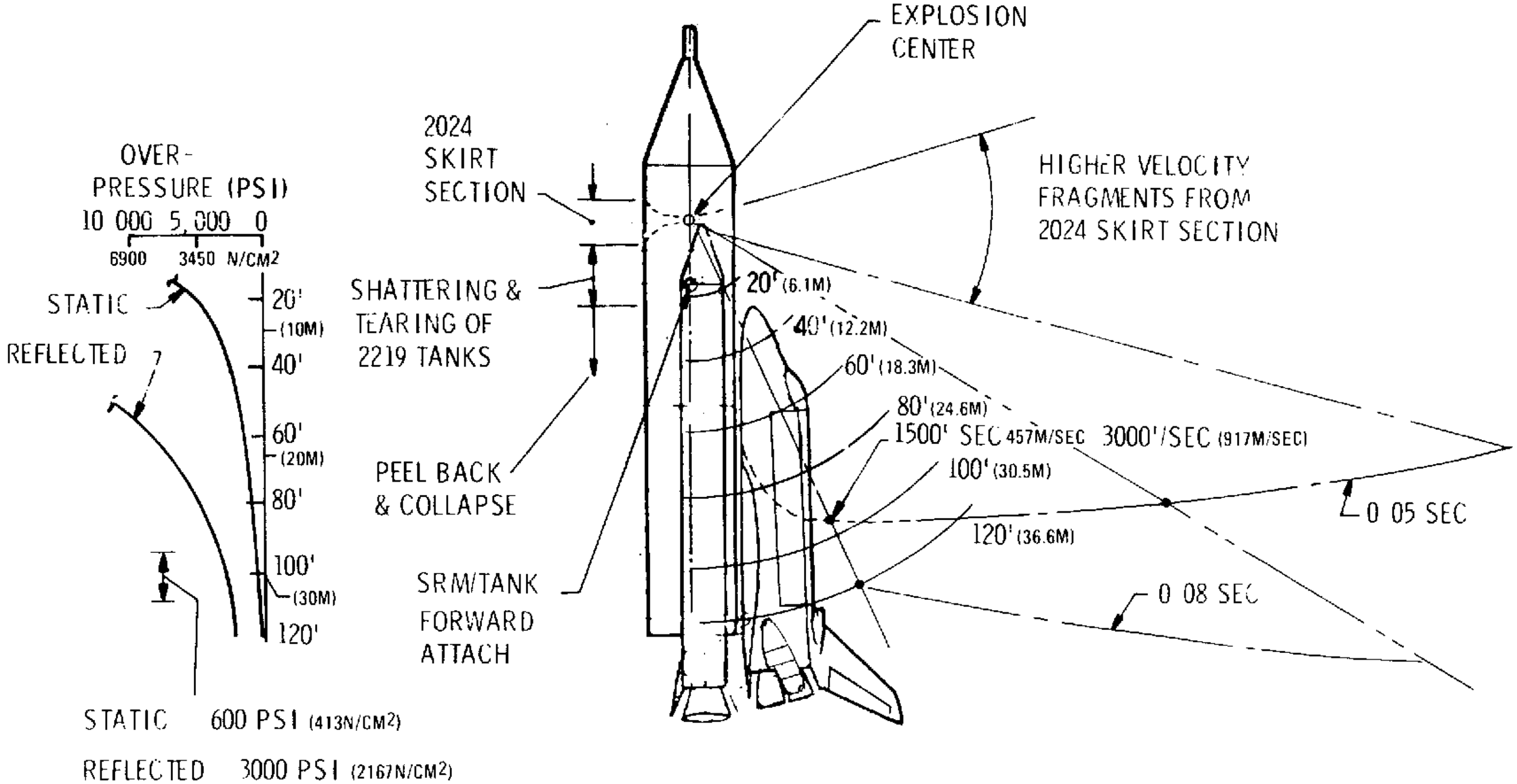


Figure 5-10. Estimated Primary Fragment Velocities and Overpressures from External Tank Explosion

5.4.2.3.2 Explosion Center 2 - Orbiter Forward Section — As indicated in Table 5-1, the overpressure and fragmentation environment from an explosion of the Orbit Reaction Control Tanks is estimated to be far less severe than that from an external tank explosion.

5.4.2.3.3 Explosion Centers 3, 4 and 5 - Rear and Aft RCS and Orbit Maneuvering Fuel Tanks — Figure 5-11 depicts the estimated path and velocities of fragments from an aft tank explosion and also shows the overpressure environment from a simultaneous external tank booster explosion. Maximum velocities of ~910 m/sec (3000 ft/sec) are estimated at the explosion source. These should be attenuated to ~610 m/sec (2000 ft/sec) after passing through shuttle orbiter structure.

5.4.2.3.4 Location of HSA within Shuttle Payload Bay — It is desirable to locate and orient the HSA within the 60 foot shuttle bay so that the blast overpressure is not excessive and the projected target area for fragments is minimized. Because of the large reflected overpressures that result from an external tank explosion (Figure 5-10) the HSA should be located as far aft in the payload bay as possible. Since the manipulator boom in the payload bay has a 15 meter (50 foot) radius, this would appear to be the most aft position possible for the HSA. At this point the maximum pressure is approximately 3440 N/cm^2 (5000 psi), well within the survivability capability of an FSA. (The pressure generated during an impact of an FSA at 88 m/sec (290 ft/second), is a 19,300 N/cm^2 (28,000 psi) which an FSA can survive (Reference 7). Overpressures generated by aft tank explosions are less than 27.5 N/cm^2 (40 psi) at the payload bay location (Reference 7).

Most of the higher velocity fragments within the payload bay resulting from an explosion will be traveling essentially in a forward or aft direction. From this it is concluded that the optimum orientation of the HSA to minimize the damage from fragmentation is one in which the HSA axis is parallel to the shuttle longitudinal axis.

The Mini-Brayton radiator, HSA structure and HSHX will afford some protection to the Heat Source by attenuating impinging fragments. It has been estimated, however, that

BOOSTER STATIC	BOOSTER REFLECTED
6.1m (20') – 3800 N/cm2 (5500 psi)	55,000 N/cm2 (80,000 psi)
9.1m (30') – 2420 N/cm2 (3500 psi)	31,000 N/cm2 (45,000 psi)
12.2m (40') – 1650 N/cm2 (2400 psi)	19,300 N/cm2 (28,000 psi)

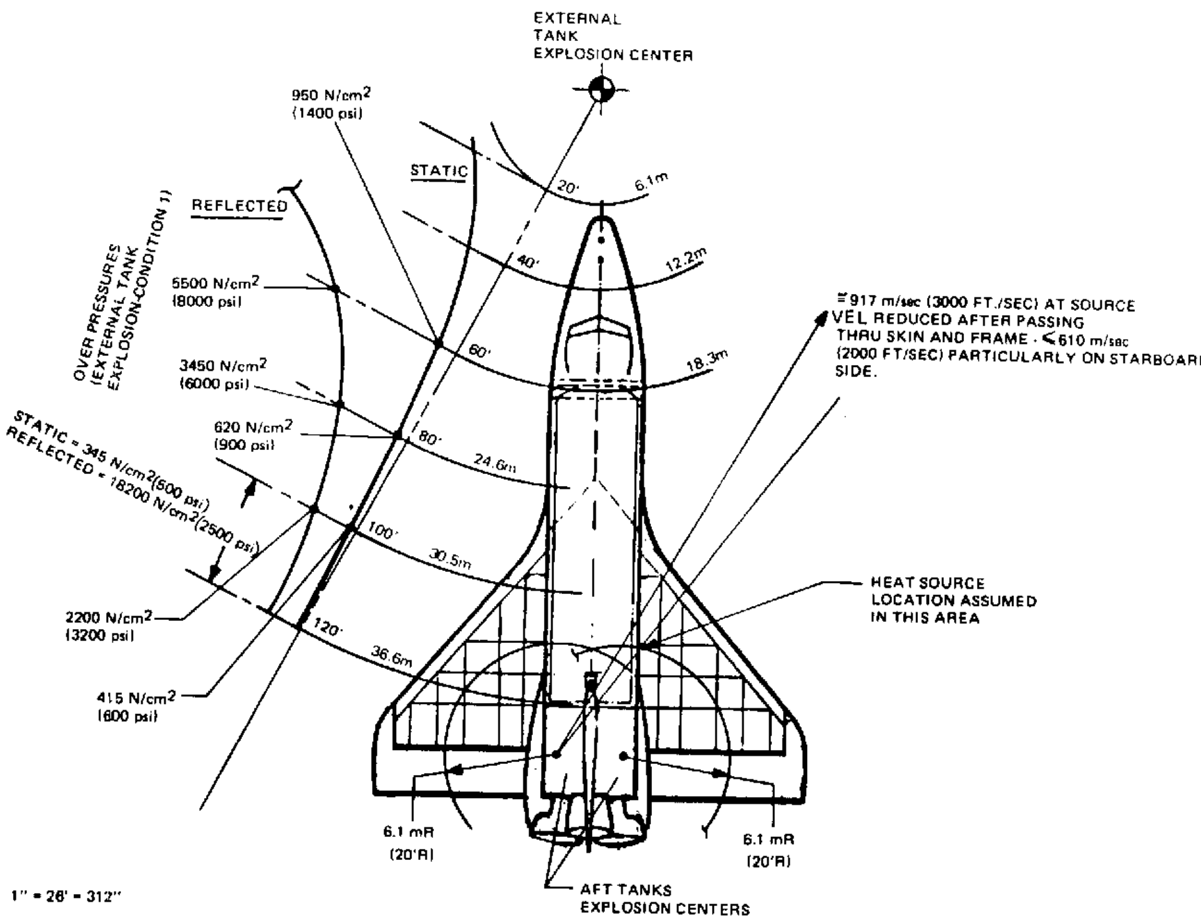


Figure 5-11. Fragmentation Environment for Aft Tank Explosions

attenuation will not be sufficient to prevent a potential radiological hazard and it is concluded that fragmentation shielding will be required. Such shielding can be designed either as an individual shield surrounding the HSA or provided as an external shield surrounding the entire Mini-Brayton power module. The latter concept will present a simpler integration problem than the former but undoubtedly will be heavier. Clearly further evaluation of the potential fragmentation environment based on a more detailed definition of shuttle structure and explosive yields is required before a final evaluation of Mini-Brayton shield requirements can be made.

5.4.3 ASCENT AND IN-ORBIT ACCIDENTS

Explosions during ascent or while in orbit will impose less severe conditions on the heat source than those which might occur during the pre-launch phase. Aborts during ascent or during orbit transfer of the Mini-Brayton to or from the shuttle can result in an unplanned re-entry and impact. The survivability of the Heat Source under these conditions is discussed in the next section.

5.4.4 RE-ENTRY

There are a myriad of potential reentry conditions that can occur as results of aborts taking place in the mission after launch. An exhaustive analysis has been conducted on the MHW-RTG program to determine the survivability of a free unencumbered Heat Source for a spectrum of reentry conditions. It has been determined (Reference 2) that the Heat Source will survive re-entry through the atmosphere with no release of isotope fuel for the following initial conditions.

1. Altitude - 121,920 m (400,000 ft)
2. Initial velocity: 7300-11000 m/sec (24,000-36,333 ft/sec).
3. Path angle to the local horizontal: 0° to -90°.

Neither failure of the aeroshell nor melting of the PICS will occur for any combination of the conditions above which include super-orbital and multiple skip reentries. In the present study a preliminary analysis was conducted to determine if fuel release would occur for reentry of a complete HSA. The assumptions made are as follows:

1. HSA is complete, but separate from Mini-Brayton Power System
2. Entry configuration is side-on stable
3. Emergency cooling has functioned properly, the doors are opened and the insulation is intact
4. Entry starts (time = 0) at 122 km (400 K feet) with a velocity of 7600 m/sec (25,000 fps) and a "down" angle of 0.05°.

These assumptions were used along with HSA weights of 68, 56 and 45 kg (150 lb, 125 lb, and 100 lb) to determine the trajectory of the HSA through the atmosphere. The geometry was held constant, yielding values of W/A of 325, 267 and 216 kg/m^2 (66.0, 54.5, and 44.0 lb/ft^2). The drag coefficient, C_d, based on cylinder geometry varies with each number and altitude as shown in Figures 5-12 and 5-13.

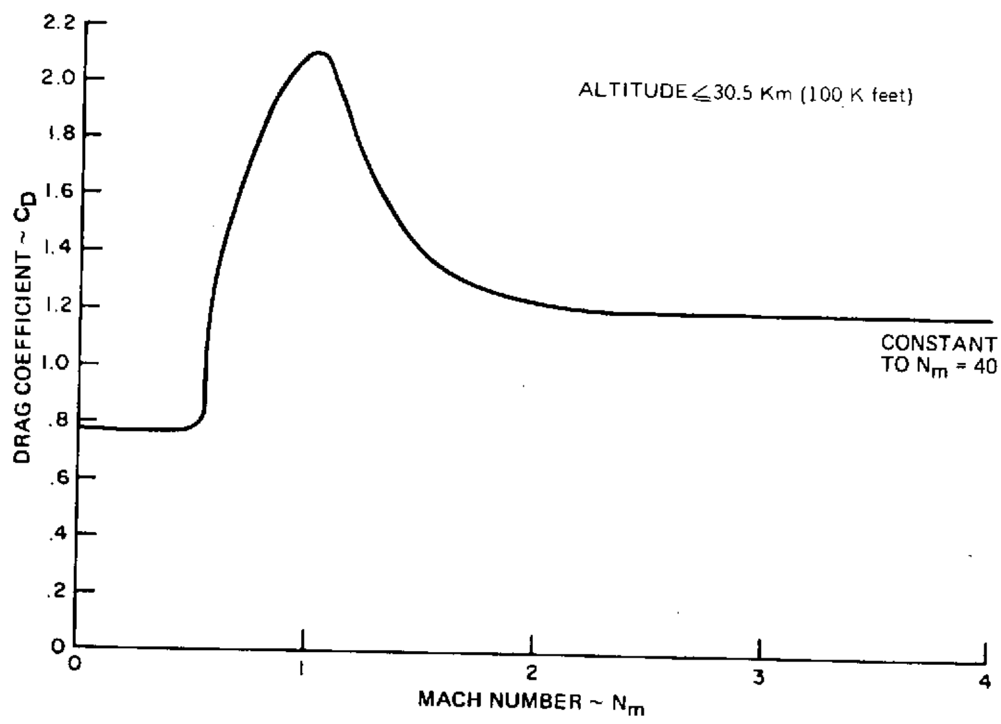


Figure 5-12. Drag Coefficient vs Mach Number-Cylinder

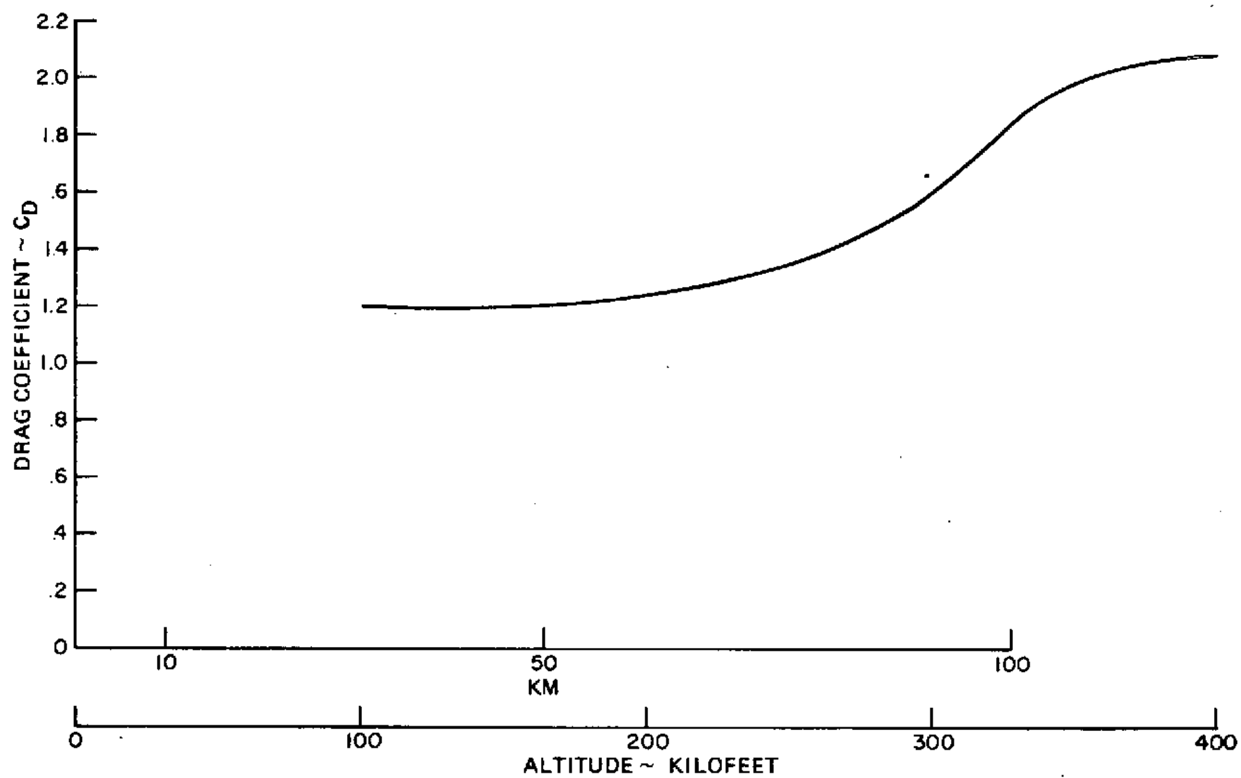


Figure 5-13. Drag Coefficient vs Altitude-Cylinder

The results of the reentry trajectory analyses are shown on Figure 5-14 which presents the altitude vs time profile. Only one curve is shown since there was no significant difference in all three profiles except at the very end of the trajectory. The heavier assembly impacts the earliest, at 867 seconds, and the lightest impacts last, at 917 seconds. However, the major deviation in these trajectories all came at low altitudes and low velocities. Therefore, thermodynamically they were not significantly different, each having similar heating profiles through the peak heating condition. To be conservative, the higher heating rate data from the heavier system was used in the analysis. Figure 5-15 presents the normalized heat flux profile based on a "spinning" cylinder. The HSA does not actually spin; this was just a means of obtaining average heat flux data more readily. The actual input to the thermal analysis program used a value twice the average rate applied to only half the surface.

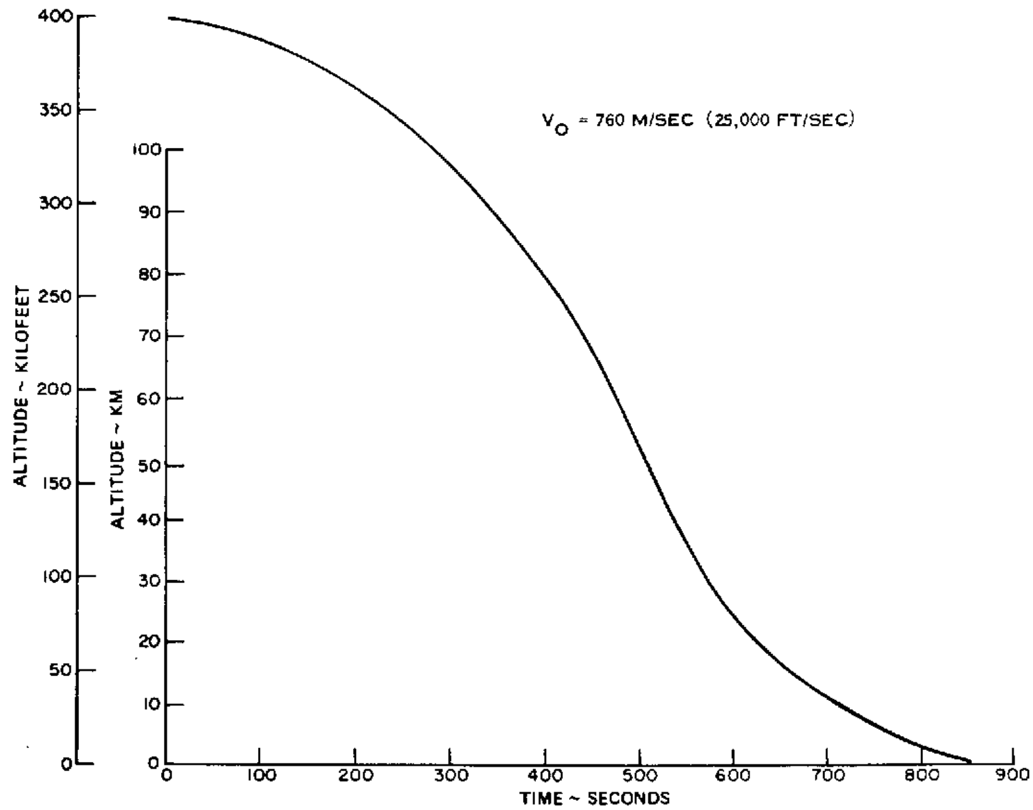


Figure 5-14. HSA Re-entry Trajectory

A 16 nodal model was used in the transient temperature analysis and the results are shown in Figure 5-16. The initial temperatures are equilibrium temperatures with the emergency cooling doors open; during the time of an orbit decay to 400,000 feet, steady state temperatures conditions would prevail. Data is given for the outer structural shell, the heat exchanger and the heat source only since the insulation burns off rapidly once the outer layer reaches its melting point. The insulation is removed in 20 seconds from the time the first section comes off.

The HSA structural container shell responds quite rapidly to the heat flux with the insulation gone. Its large mass in conjunction with the short time left before peak heating, results in a maximum temperature well below its melt point (2800° K (4600° F)).

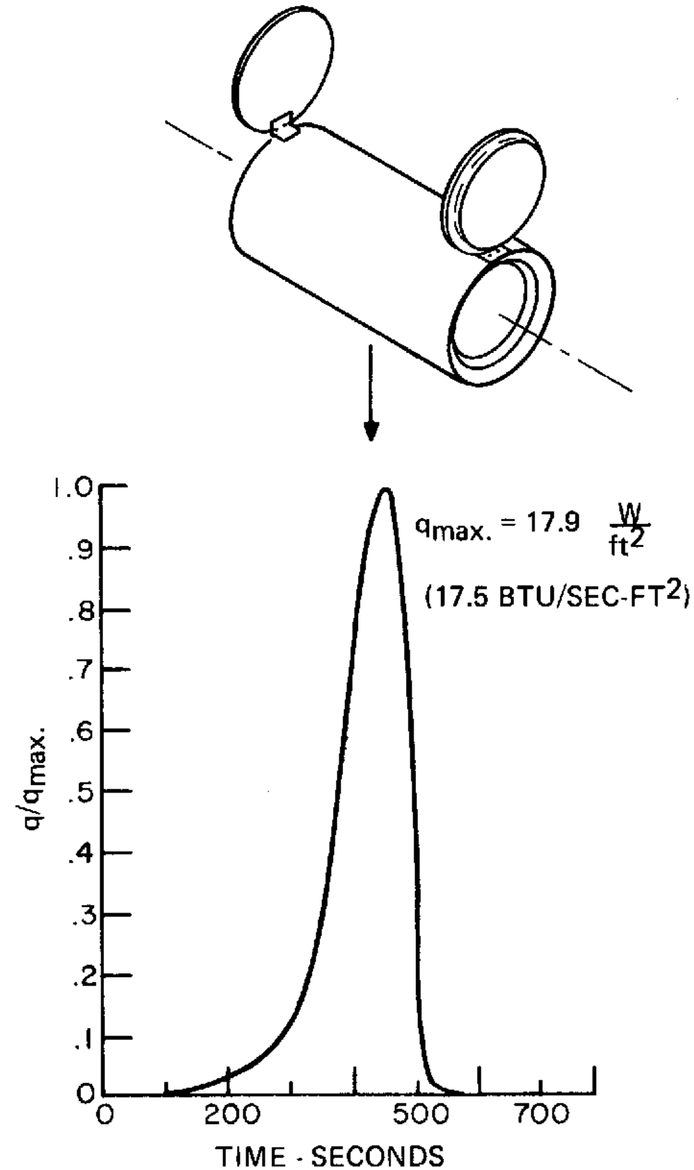


Figure 5-15. AERO Heating Profile - Heat Source Assembly

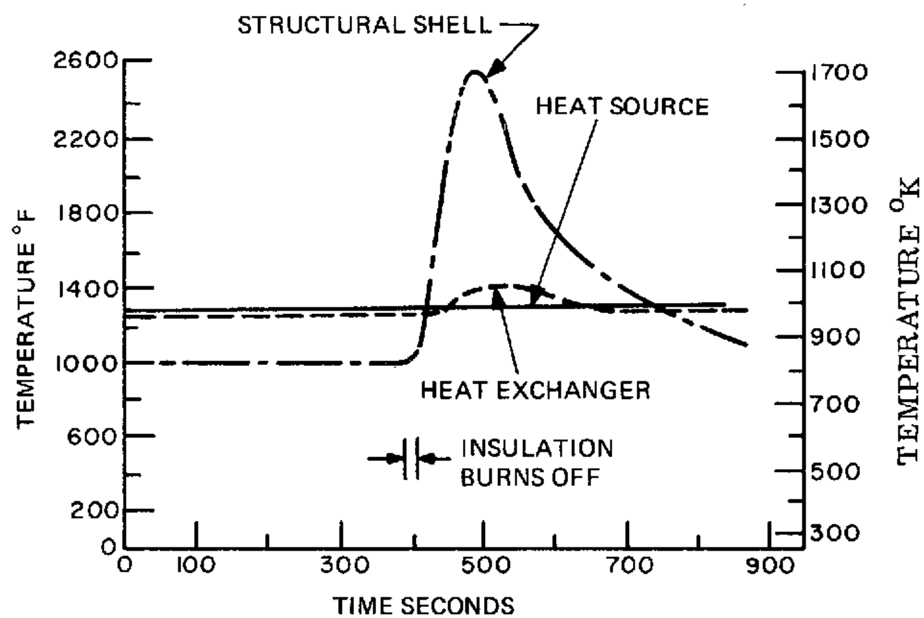


Figure 5-16. HSA Re-entry Temperature Profile

The thermal inertia of the structure provides ample protection for the heat exchanger and heat source which do not show any significant change in temperature throughout the re-entry period.

It can be concluded from this simplified analysis that the margin exhibited in the response of the heat source shows that even if heating rates are significantly higher, the heat source temperature will still be well within safe limits that preclude fuel release.

5.4.5 MINI-BRAYTON SAFETY GUIDELINES AND REQUIREMENTS

This section presents a summary of the major safety design requirements and guidelines that directly affect the HSA design and shuttle interfaces. Detail requirements and guidelines are given in Appendix B in a format which relates the requirement or guideline to a mission phase and operational function, and allocates the requirement to particular hardware or operations.

1. Heat Source Safety Design Requirements
   - a. Provide fireball, solid fire and blast over-pressure protection to preclude any radiological hazard in the event of an on-pad explosion (the most severe explosion environments).
   - b. Provide the capability of the Heat Source to withstand the reentry environment from earth orbital decay in a free body (HS alone) configuration, an HSA configuration and a power module configuration. Included is the capability of the Heat Source to withstand impact as a free body on a hard surface at terminal velocity. Satisfaction of this design requirement will assure that no isotope fuel release to the biosphere occurs during an unplanned reentry.
   - c. Provide the capability of the Heat Source to survive a shuttle crash landing. Since crash landing velocities have not yet been defined it must be determined at a later date that no radiological hazard would occur in the event of this accident mode.
   - d. Limit exposed surface temperatures to less than $466.5^{\circ}K$ ($380^{\circ}F$) during pre-launch on pad operations to prevent accidental ignition of booster fuels.
   - e. Provide an emergency cooling system to limit Heat Source temperatures to safe levels at any time during the mission in the event of any failure

that could cause a Heat Source overtemperature. Typical failures that might occur are shuttle operational failures that delay deployment and operation of the Mini-Brayton system after launch, failure of Mini-Brayton Power Conversion Components in orbit, forced landing of the shuttle, etc.

2. Shuttle Safety Guidelines

   a. Provide a heat sink capability for rejecting 7200 watts of heat from the Mini-Brayton system during any mission phase when the system or the Heat Source may be in the payload bay.

   b. Provide at least a two (2) week supply of coolant for auxiliary cooling of the Heat Source following a forced landing of the shuttle.

SECTION 6

HSA DESIGN REQUIREMENTS

6.1 OPERATIONAL REQUIREMENTS

The HSA shall be designed to be used singly, or in multiples of two or three in a parallel configuration, for the following conditions:

	Number of HSA Units in Parallel		
	1	2	3
HSHX Inlet Temperature °K (°F)	989 (1320)	990 (1322)	992 (1326)
HSHX Outlet Temperature °K (°F)	1153 (1615)	1153 (1615)	1153 (1615)
Flow Rate Kg/sec (lb/sec)	.0565 (.125)	.113 (0.249)	.175 (0.387)
Outlet Pressure N/cm^2 (psia)	24.7 (35.9)	50.2 (72.8)	78.4 (113.9)
Maximum Pressure Drop Across HSHX $\frac{\Delta P}{P}$	.006	.003	.002

As a design goal, the outer surface (emissivity sleeve) of the heat source shall not exceed 1283°K (1850°F) during steady state operation. The same heat source used in the MHW RTG can operate at 1366°K (2000°F), hence this goal provides a healthy design margin.

The HSA shall be designed for a 5 year operational mission in space vacuum with the capability of removing the heat source in space as indicated in paragraph 1.5.

6.2 NON-OPERATIONAL REQUIREMENTS

During non-operational periods at the launch site, the Auxiliary Cooling Subsystem must be capable of limiting any surface of the HSA which is exposed to the external environment to temperature not exceeding 466.5°K (380°F). This is a safety requirement (see paragraph 5.1) to preclude accidental ignition of spacecraft or booster fuels. Furthermore the ACS must be capable of limiting the outer graphite surface of the Heat Source to a temperature not exceeding $\sim$500°K (440°F) to prevent oxidation of the graphite.

If the Mini-Brayton is started up on the pad, an inert cover gas for the Heat Source must be provided to preclude oxidation of the graphite sleeve at operating temperatures. At the same time the safety requirement pertaining to exposed surfaces being less than 466.5°K (380°F) must be satisfied.

6.3 EMERGENCY COOLING REQUIREMENTS

The Emergency Cooling Subsystem must be capable of limiting Heat Source Temperatures to safe levels at anytime during the mission in the event of any failure that could cause a Heat Source overtemperature. Typical of such failures are delays in deploying and starting up the Mini-Brayton system after launch, failure of power conversion components such as the BRU, in orbit, crash landing of the shuttle in remote areas with the HSA aboard, etc.

Specifically, the Emergency Cooling Subsystem must be capable of limiting the outer surface of the Heat Source to a maximum steady state temperature of no greater than 1490°K (2223°F). This surface temperature results in a PuO_2 - Iridium interface temperature of a Heat Source Post Impact Containment Shell of 1773°K (2732°F); this has been established on the MHW program as the maximum permissible long term PICS temperature.

For a short transient duration of the order of 5 minutes, the outer Heat Source temperature may be permitted to reach a maximum of 1922°K (3810°F). This temperature corresponds to a maximum PICS temperature of 2372°K (3810°F) which is the upper test limit conducted on the MHW program.

6.4 GROUND TEST REQUIREMENTS

The HSA shall be designed for a continuous 2 year ground test (in the Power System configuration.) It would be highly desirable to conduct the test completely in an air environment. If, however, this compromises the operational performance, either an inert gas or vacuum environment will be provided for the HSA.

SECTION 7
MATERIAL SELECTION

The high temperature environment within the Heat Source Assembly insulation blanket enclosure dictates careful selection of materials for HSA components. The considerations herein apply to the Heat Source Heat Exchanger, its manifolding and headers, the Auxiliary Cooling System manifolding, the Heat Source and HSHX support structure, the HSA support structure and in general to all components inside the insulation enclosure.

7.1 SELECTION CRITERIA

7.1.1 REQUIREMENTS

The major requirements that materials for the Heat Source Heat Exchanger and structural components of the HSA must satisfy are as follows:

1. Materials must be capable of sustaining a vacuum environment for at least five years. The effects of a high temperature vacuum environment on materials, i.e., evaporation, is a major selection criteria.
2. Material must exhibit and maintain requisite strength at operating temperatures under the conditions of (1) above. High temperature components must be capable of operating at 1255°K (1800°F) in vacuum. Melting temperature must be substantially higher.
3. Materials must be capable of undergoing multiple thermal cycles between room temperature and operational temperatures during ground tests. Fifty cycles has been selected as a preliminary criterion.
4. HSHX materials must be compatible with the Mini-Brayton working fluid, helium-xenon.
5. All HSA materials must be mutually compatible with each other and with other interfacing materials in the Mini-Brayton Power Conversion System.
6. The HSA, as designed for space flight operation, must be capable of undergoing a continuous 2-year ground test. This requirement is not interpreted as a limitation on test approach. For example, if it is deemed appropriate and feasible, flight equipment can be tested in a vacuum chamber or in an inert environment.
7. Materials must not be adversely affected by the nuclear radiation from the isotope fuel.

7.1.2 SELECTION CRITERIA

Candidate materials that meet the above requirements are compared and evaluated based on the following criteria.

1. Weight - Minimum weight is a goal. Both material density and structural strength, in particular creep strength at operating temperature, determine the weight of an HSA component. Structural gages are governed by the strength of the material, and weight is proportional to the product of density and material thickness. One percent creep stress at operating temperature over five years is used to size components. In some instances fabrication considerations may be the limiting factor on structural gages and in these cases it becomes a prime factor in determining weight.

2. Structural Stability - Because of the 5-year operation requirement at high temperature, effects of stress time deformation resulting from long term creep of the structure is a very significant design consideration in material selection. In addition, large temperature differentials between structural components dictate a strong preference for low thermal expansion materials. Optimum material selection will minimize thermally induced stresses both during operation and during the transient warm-up period prior to operational conditions.

3. Fabricability - The high reliability required for five-year power operation is directly related to the complexity and reliability of the fabrication of high temperature components such as the HSHX, especially for the class of materials applicable to the HSA design. The ease of forming and working to required shapes, the joining characteristics, especially weldability and joint properties, the availability and long term compatibility of braze alloys, and general fabrication experience are all factors in the selection of materials that will result in a highly reliable fabricated assembly.

4. Thermo-optical Properties and Coatability on Surface Treatments - A HSA design goal is to minimize Heat Source operating temperature. The emissivity of the HSHX surrounding the Heat Source will have a direct effect on the Heat Source temperature, consequently a high HSHX emissivity is desirable. The emissivity of the parent material and/or the ability to coat or treat the HSHX surface to obtain a stable high emissivity is therefore a consideration in material selection.

5. Cost and Availability - Material cost is a significant factor if there are large differences between material costs and if these costs are a significant fraction of the overall HSA cost. Since the MHW heat source will cost on the order of 2 million dollars, a factor of 2.5% or $50,000 has been selected as the threshold at which material costs are considered significant.

Availability is a consideration in so far as the stock types (sheet, tubes, etc.) available and the development status of the material. The prime candidates considered are available in the forms required for HSA fabrication, hence no problems in this regard are anticipated.

6. Material Characterization - The extent of existing material characterization (known properties and behavior) at the particular temperature and lifetime duration of the HSA is another factor in selecting a material. The degree of data available is directly related to the amount of experience with the material. It is recognized that where specific data is lacking for an otherwise attractive candidate, the data can be provided by an appropriate test program. In this regard, lack of complete material characterization has not been a criteria for eliminating a candidate and where necessary data has been extrapolated to make preliminary evaluations.

7.1.3 CANDIDATE MATERIALS

The high operating temperatures of the HSA limit candidate materials to three classes of material, viz:

1. Superalloys
2. Refractory alloys
3. Refractory noble metals and alloys.

Superalloy candidates are classified as cobalt base alloys and nickel base alloys. Refractory alloy candidates are classified as columbium base alloys and tantalum base alloys. The refractory noble metal and alloys are rhodium, iridium, platinum and the binary and ternary platinum alloys. The chemical compositions of the materials considered for the HSA are given in Table 7-1a, b and c. This initial list was limited to the medium strength refractory alloys which exhibit adequate strength for the HSA design and which are easier to work than the higher strength refractory alloys. The superalloy candidates are well representative of the spectrum of alloys which are commonly used for high temperature applications.

TABLE 7-1. CANDIDATE MATERIAL COMPOSITIONS

TABLE 7-1a. SUPERALLOY COMPOSITION (WEIGHT PERCENT)

Alloys \ Elements	ThO_2	C	Mn	Cr	Ni	W	Fe	Si	Co	La	Cb	Mo	Al	S	Cu	Ti
Cobalt Base Alloys																
HA-25 (L-605)	--	.05-.15	1.0-20	19.0-21	9.0-11.0	14.0-16.0	3.0	<1.0	Bal	--	--	--	--	--	--	--
HA-188	--	.08	0.75	22.0	22.0	14.0	1.5	0.20	Bal	.08	--	--	--	--	--	--
Nickel Base Alloys																
Hastelloy-X	--	.05-.15	1.0	20.5-23	Bal	.2-1.0	17-20	1.0	--	--	--	8-10	--	--	--	--
Inconel-750	--	.04	0.70	15.0	Bal	--	6.75	0.30	--	--	.85	--	.80	.007	.05	2.5
TD Nickel	2				Bal											

TABLE 7-1b. REFRACTORY ALLOY (WEIGHT PERCENT)

Alloys \ Elements	Cb (Nb)	Zr	Hf	Ta	Y	Ti	W	C
Columbium (Niobium) Base Alloys								
Cb-1 Zr	Bal	0.08-1.2	--	--	--	--	--	--
Cb-129Y	Bal	0.5	9.0-11	0.5	1.0-0.4	--	9.0-11	--
Cb-103	Bal	0.7	10.0	0.5	--	0.7-1.3	0.5	--
FS-85	Bal	0.6-1.1	--	25-29	--	--	10.0-12	--
Cb-752	Bal	2.0-3.0	--	--	--	--	9.0-11	--
Tantalum Base Alloys								
T-111	--	--	1.8-2.4	Bal	--	--	7.0-9	--
T-222	--	--	2.2-2.8	Bal	--	--	9.6-11.2	.008-.0173
Ta-10W	--	--	--	Bal	--	--	9.0-11.0	--

TABLE 7-1c. REFRACTORY NOBLE METALS AND ALLOY COMPOSITION (WEIGHT PERCENT)

Metal/Alloy \ Elements	Rh	Ir	Pt	W
Binary Pt Alloys				
Pt-10Rh	10		90	
Pt-20Rh	20		80	
Pt-30Rh	30		70	
Pt-25Ir		25	75	
Ternary Pt Alloys				
Pt 26Rh 8W	26		66	8
Pt 30Rh 10W	30		60	10

7.2 SUPERALLOYS

7.2.1 EVAPORATION PROBLEM

For long term missions (five years or more) a general rule dictates that materials should not be used at temperatures above which their vapor pressure exceeds 10^{-7} torr. In examining the vapor pressure of the elements listed below in Table 7-2, that are contained in the superalloys, it can be seen that they would be limited to short time missions in the vacuum of space at temperatures in excess of 1311° K (1900° F). Although this temperature is higher than anticipated HSA operating temperatures, it is considered a reasonable criterion for evaluation. Alloys containing chromium, nickel, iron or manganese will require a protective coating to suppress excessive evaporation in space. The data given in Figure 7-1 (Reference 9) for example, indicates that the continuous evaporation losses from HA-25 (L-605) and Inconel at 1145° K (1600° F) and 1255° K (1800° F) respectively, constitute loss rates higher than can be tolerated for a five-year mission.

TABLE 7-2. VAPOR PRESSURE OF ELEMENTS

Element	Vapor Pressure Torr at 1311° K (1900° F)
Manganese	10^{-1}
Chromium	2×10^{-5}
Nickel	10^{-6}
Iron	10^{-6}
Cobalt	3×10^{-7}
Titanium	4×10^{-8}
Platinum	10^{-11}
Columbium	10^{-14}
Zirconium	10^{-14}
Hafnium	10^{-15}
Tantalum	10^{-15}
Tungsten	10^{-15}

Based on the composition of HA-188 and Hastelloy-X it can be concluded that their evaporation rate falls within the range given in Figure 7-1. The elements which have the highest evaporation rate are chromium, nickel and manganese and since their chemical activity and solid solutioning characteristics are high, it is possible that they will degrade surrounding materials or change their properties. Figure 7-1 also shows that the loss rate becomes constant after about 50 hours. This would indicate that the rate of evaporation of the higher vapor pressure elements becomes diffusion rate limited.

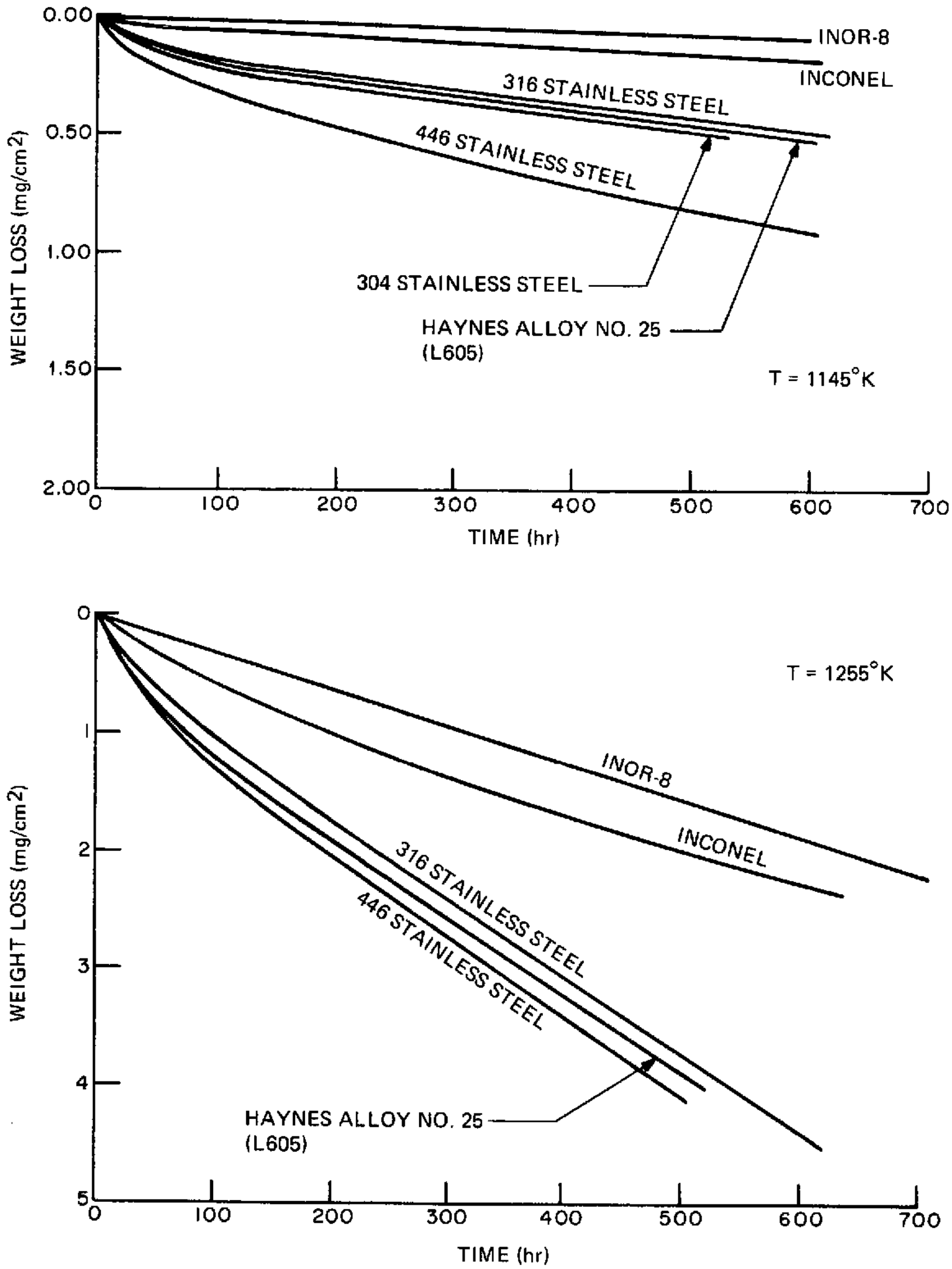


Figure 7-1. Evaporation Losses of Iron, Nickel, and Cobalt-Base Alloys (at 872 and 982° C at approximately 5 x 10^{-7} to 5 x 10^{-9} torr.)

The vapor blockage phenomena of an enclosed configuration like the HSA may reduce evaporation rates. However this cannot be accurately predicted and consequently cannot be relied upon as a design feature. Furthermore since the vapor pressure of the evaporating constituents are highly temperature dependent, temperature differences of the order of 100° K within the HSA enclosure may prevent a vapor blockage phenomenon from occurring. For example, chromium vapor pressure drops from 2.5×10^{-6} torr to 1×10^{-7} with a temperature change from 1273° K to 1173° K. Chromium would evaporate from a "hot" surface in the HSA and recondense at a "cooler" surface, providing a path within the HSA for the evaporation process.

Formation of oxides on the surface of superalloys during prelaunch would have the initial effect of slowing the rate of evaporation in space. At temperatures above 1200° K (1700° F) in vacuum, chromium oxide (Cr_2O_3) undergoes dissociation so that the characteristic rate of evaporation would be re-established in time. It is possible to inhibit evaporation by plasma arc coating the surface of superalloys with a high emissivity coating such as Radifrax, RC 356. This coating was successfully applied to the surface of the SNAP 27 heat source, fabricated from HA25 (L-605) alloy, and to the SNAP 27 hot frame fabricated from Inconel 102, primarily to provide a high emissivity (.85 to .9) and to inhibit evaporation. The composition of this coating is the following:

Iron Titanate . . . . 60 w/o (weight-percent)
Calcium Titanate . . . . 30 w/o
Silicon Dioxide. . . . . 10 w/o

The degree to which the above coating will inhibit evaporation at temperatures above 1200° K (1700° F) remains to be experimentally established.

7.2.2 SUPERALLOY OXIDATION

Oxidation of superalloys takes place in air above 978° K (1300° F). As the surface oxide builds up in thicknesses to about 0.050 to 0.075 mm (0.002 to 0.003 inches), the high density oxide layer forms a barrier against further oxidation of the substrate metal. While this characteristic would permit the use of superalloys for ground testing in air environments, the instability of the oxides in vacuum at the HSA operational temperature would preclude dependence upon it as a barrier to evaporation in space.

The oxidation rates of the candidate superalloys at 1366° K (2000° F) are given below:

Alloy	Rate in Dry Air 1366° K (2000° F)
HA-188	20 mpy*
HA25 (L-605)	92 mpy
Hastelloy-X	25 mpy
Inconel-750	103 mpy
TD Nickel	150 mpy

*Mils per year

The buildup of thick oxide layers during a two-year ground test would be undesirable since it could affect performance. Figure 7-2 shows a comparison of the oxidation resistance of three alloys as a function of temperature. The HA-188 alloy possesses the highest stability in an oxidizing environment. While Inconel-625 is not shown, its composition indicates that it will perform about the same as Hastelloy-X under the same conditions.

7.2.3 MECHANICAL PROPERTIES

Typical mechanical properties of superalloys are given in Table 7-3. Generally the superalloys exhibit high strength at moderately high temperatures, however, the strength falls off rapidly as the temperature increases beyond 1145° K (1600° F). The development of TD Nickel, containing two percent (by volume) thoria, imparts useful mechanical properties at elevated temperatures. Beyond ~1366° K (2000° F) the tensile strength of TD Nickel falls off slowly and remains well beyond the strength of HA-25 HA-188, for example. However in the operating temperature range of the HSA, the tensile strength of Haynes alloy is greater hence there appears to be no advantage of considering TD Nickel for this application. The higher ductility of Haynes alloys renders them more fabricable than TD Nickel and capable of withstanding the higher induced stress with lower rates of fatigue.

Of the candidate superalloys, the most attractive is HA-188. It possesses the highest strength at HSA operating temperatures, has excellent ductility and exhibits the lowest

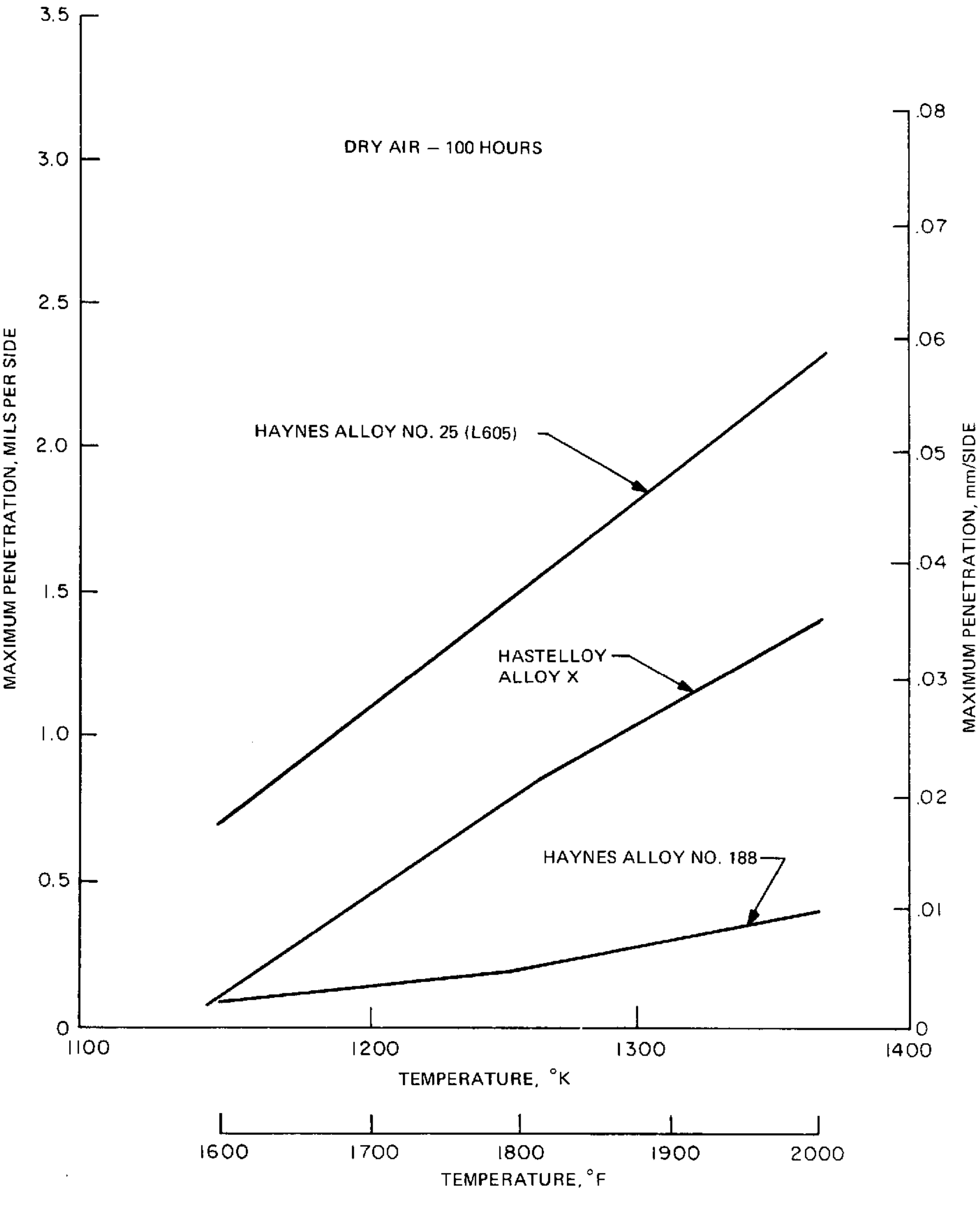


Figure 7-2. Oxidation Resistance of Superalloys

TABLE 7-3. MECHANICAL PROPERTIES OF SUPERALLOYS

Alloy	Density gm/cm^3	Density lb/in^3	Melting Point oK	Tensile N/cm^2	Tensile psi	Yield N/cm^2	Stress psi	Elongation %	Expansion Coefficient 10^{-6} cm/cm °C	Expansion Coefficient 10^{-6} in/in/° F	Creep Data (1) Rupture 10^3 N/cm^2	Creep Data (1) Rupture ksi	Creep Data (1) 1% 10^3 N/cm^2	Creep Data (1) 1% ksi
HA25 (L-605)	9.14	.33	1643	23100	33500	12600	18200	40	16.9	9.4	0.9	1.3	0.55	
HA-188	9.14	.33	1643	25400	36800	15500	22500	72	17.8	9.9	0.9	1.3	0.55	
Inconel-750	8.24	.298	1673	6890	10000	3450	5000	90	17.8	9.9	<0.35	<0.5	-	-
Hastelloy-X	8.23	.297	1658	13780	20000	11700	17000	45	16.7	9.2	0.55	0.8	0.35	0.5
TD Nickel	8.92	.322	1727	13780	20000	13780	20000	10	15.3	8.5	4.85	7.0	4.15	6.0

(1) 40,000 Hr. Creep Estimate

rate of oxidation. Creep strength data for the HA-188/HA-25 used in further design trades is plotted as a function of time at 1255°K (1800° F) in Figure 7-3; extrapolation of data to 5 years is required.

7.3 REFRACTORY ALLOYS

Columbium and tantalum refractory alloys exhibit very high melt temperatures and good strength characteristics at elevated temperatures beyond 1144°K (1600° F). Their tensile strength does not fall off as rapidly as the superalloys. In general these alloys cannot be used in an air oxidizing environment at temperatures in excess of 700°K (800° F). Therefore, it is necessary to provide an inert gas or vacuum environment in which to carry out ground system testing. Alternately, oxidation can also be prevented by coating these alloys with a defect free oxidation resistant coating. However, the reliability of such a coating especially for a long term (2 year) ground test is questionable. Thermal cycling would also have a deleterious effect on coating reliability. The alloys however, can be used in space vacuum at temperatures up to 1922°K (3000° F) without significant weight loss and consequently are attractive for long life, high temperature operation in space. The characteristics of the refractory alloys are discussed below.

7.3.1 MECHANICAL PROPERTIES

Mechanical properties of the refractory alloys at elevated temperatures are given in Table 7-4. Some representative strength data is plotted in Figures 7-4, 7-5 and 7-6 for Cb-103, C-129Y and T-111, respectively. They all have reasonably high strength

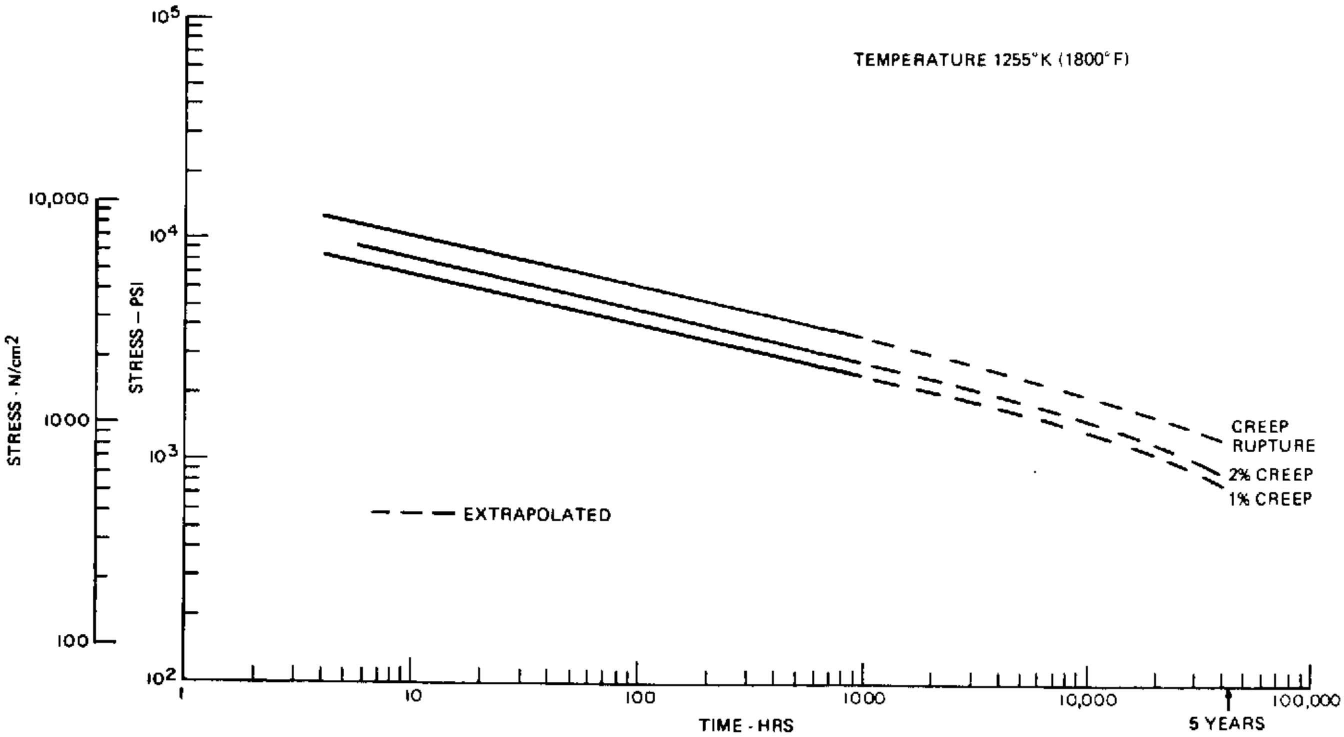


Figure 7-3. HA-25/HA-188 Creep Properties

TABLE 7-4. MECHANICAL PROPERTIES OF REFRACTORY ALLOYS
1255° K (1800° F)

Material \ Characteristic	Density gms/cm^3	Melting Temperature °K	Strength: Tensile 10^3 N/cm^2	Tensile KSI	Yield 10^3 N/cm^2	Yield KSI	Elongation %	Coefficient of Expansion 10^{-6} cm/cm/°C	Coefficient of Expansion 10^{-6} in/in/°F	Creep Data(1): Rupture 10^3 N/cm^2	Rupture KSI	1% 10^3 N/cm^2	1% KSI
Cb-1Zr	8.57	2680	18.6	27	6.9	10	20	6.34	3.8	4	5.8	1.24	1.8
Cb-129Y	9.49	2671	36	52	22	32		7.75	4.3	5.85	8.5	1.86	2.7
Cb-103	8.85	2622	24	35	14.5	21		7.75	4.3	4	5.8	1.24	1.8
Cb-752	9.02	2477	38	55	24	35		7.75	4.3	6.9	10	2.28	3.3
T-111	16.8	3255	38	55	24	35		6.3	3.5	13.8	20	6.9	10
T-222	17.0	3294	58.5	85	28	41		6.3	3.5	24.1	35	13.8	20
Ta-10W	16.9	3308	48.5	70	26.2	38		5.4	3.0	17.2	25	10.3	15

(1)40,000 HR Creep Estimate

at HSA operational temperatures. Because of lower modulus and yield properties, the columbium alloys can be more readily fabricated into the design shapes of the HSHX than the tantalum alloys. The higher ductility of columbium also permits the HSHX to respond more readily to cyclic power system operation during ground tests.

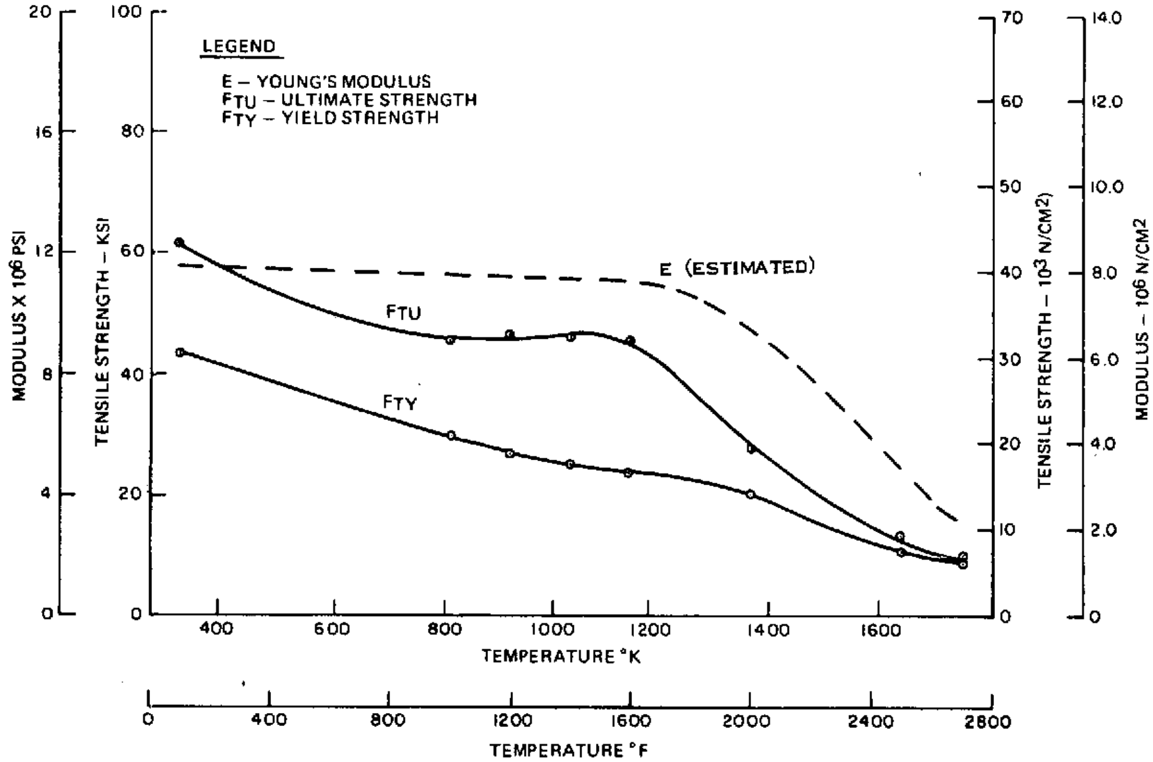


Figure 7-4. Tensile Properties Cb-103-WAH Chang Data

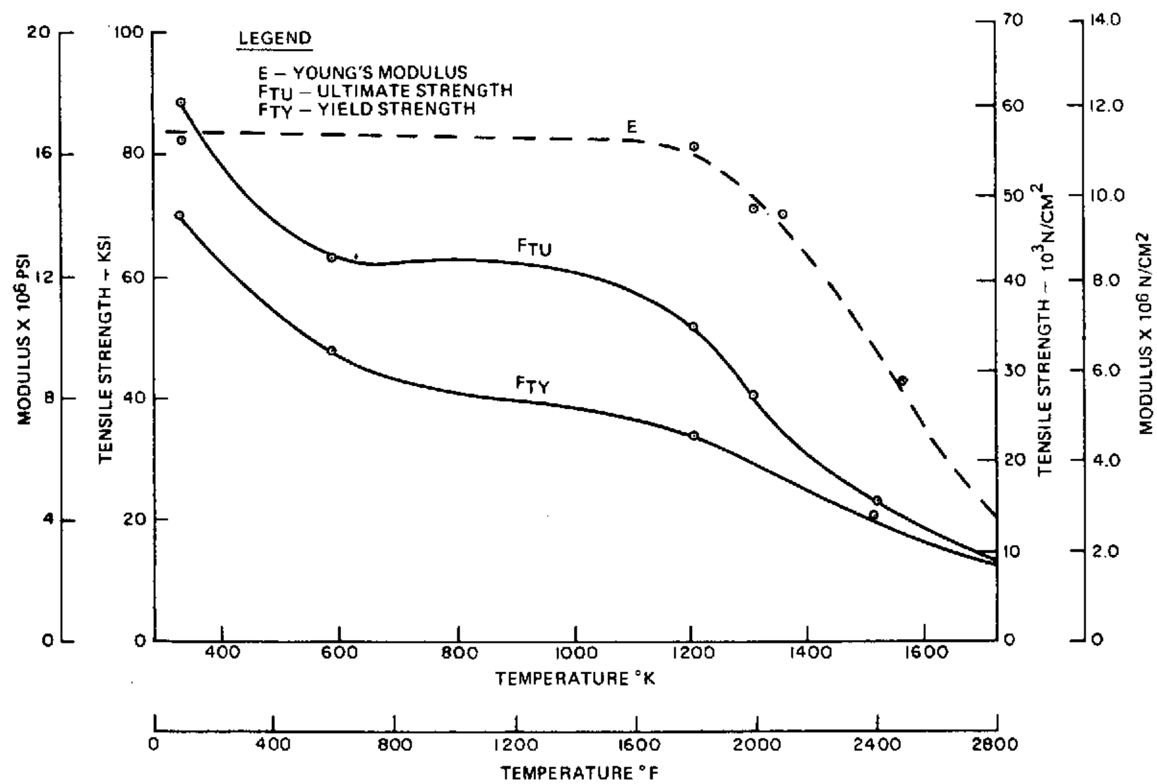


Figure 7-5. Tensile Properties Cb-129Y-WAH Chang Data

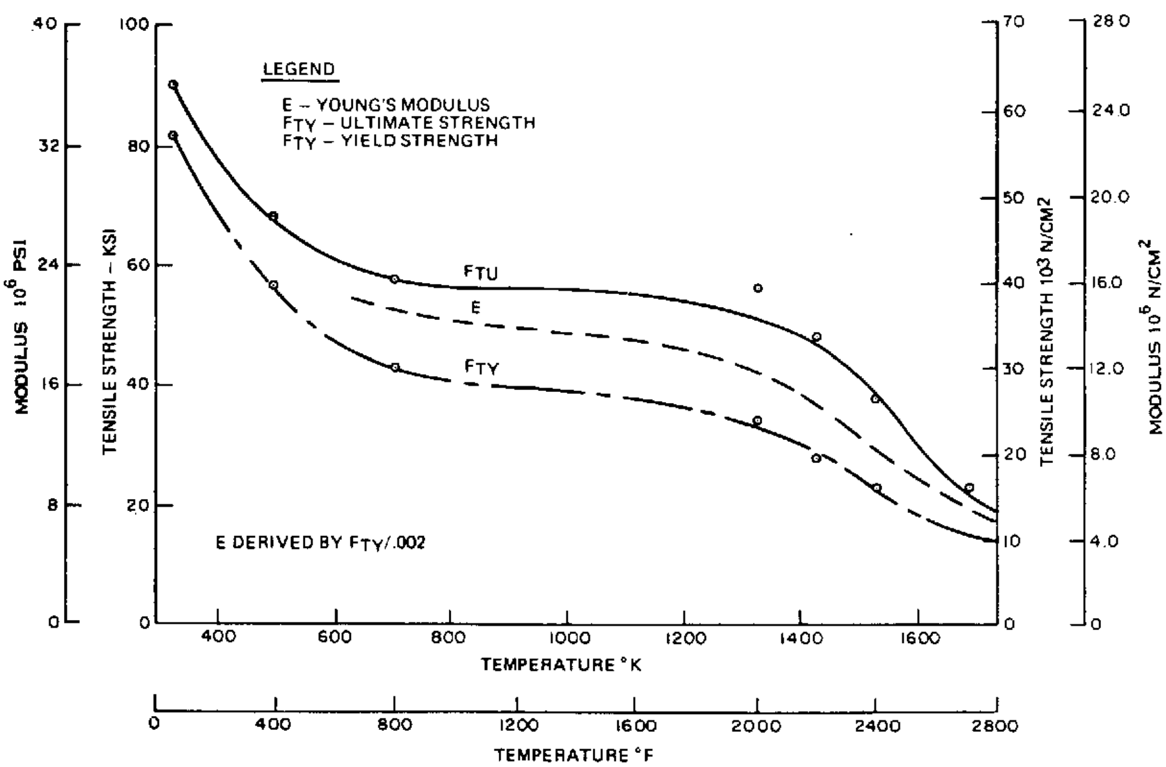
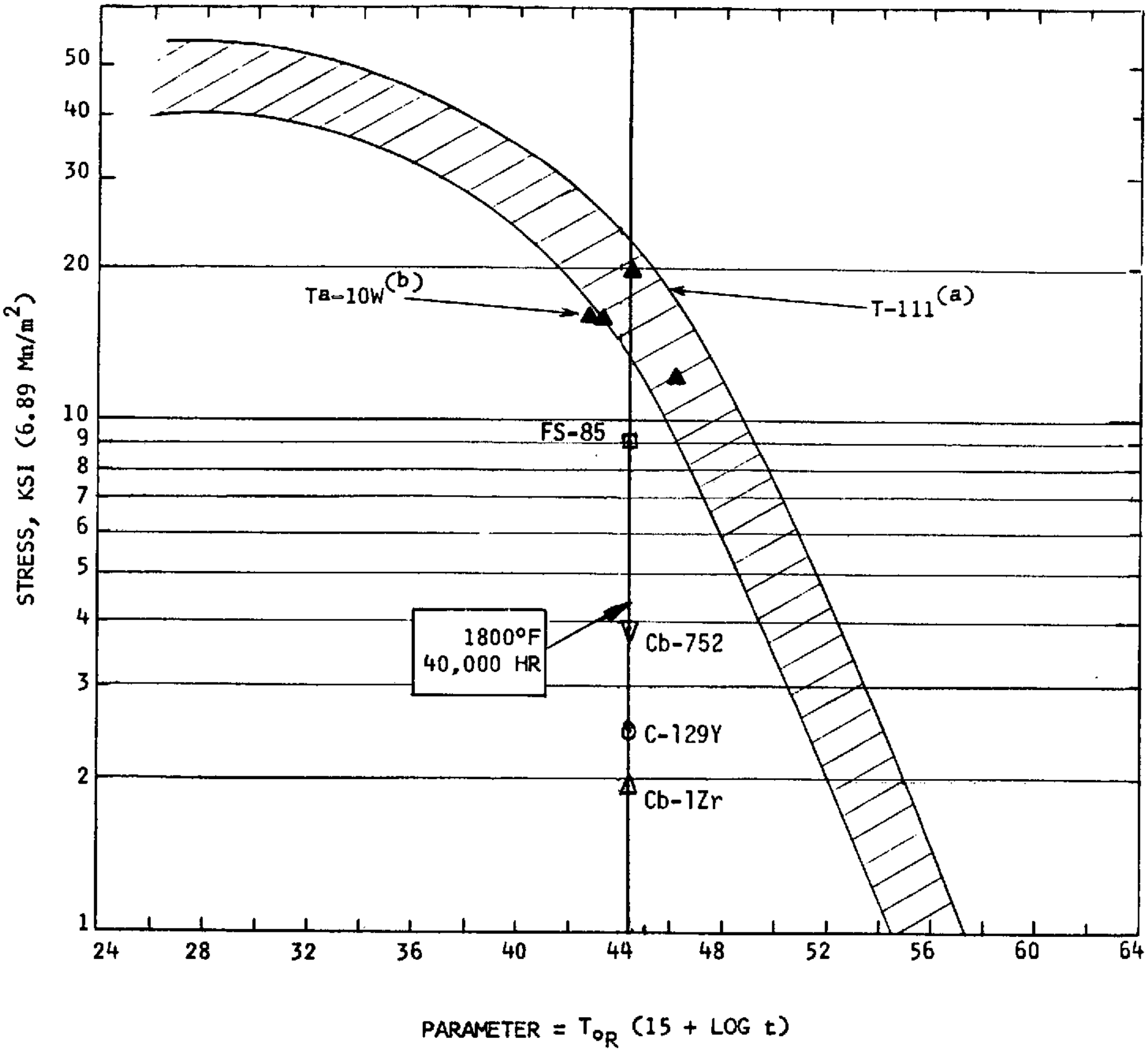


Figure 7-6. Tensile Properties T-111 Cold Rolled Recrystallized-WAH Chang Data

7.3.2 CREEP DATA

As indicated in paragraph 7.1, long term high temperature creep strength is an important trade off parameter in the selection of HSA materials. Some representative data for refractories is given in Figure 7-7. The shaded area is the region that applies to T-111; data points for Ta-10W are shown within the band. Also plotted on Figure 7-7 are individual data points for some of the columbium alloys. It should be pointed out that some of the test data was obtained by subjecting the materials to accelerated creep tests at higher than 1800° F for shorter durations of time than 10,000 hours to obtain an equivalent Larson Miller parameter (abscissa of the plot). Although data for Cb-103 is not shown, its creep strength is expected to be similar and slightly better than Cb-1Zr. It is evident from the data, that the tantalum base alloys exhibit greater creep strength than the columbium base alloys, but their higher densities and lower ductility offset this advantage.



(a) SHEFFLER, K.D., "GENERATION OF LONG TIME CREEP DATA ON REFRACTORY ALLOYS AT ELEVATED TEMPERATURES", FINAL REPORT CONTRACT NAS 3-13469, NAS CR-72997, TRW ER-7541, TRW MATERIALS TECHNOLOGY LABORATORIES, MAY 20, 1971.

(b) SHEFFLER, K.D., "GENERATION OF LONG TIME CREEP DATA ON REFRACTORY ALLOYS AT ELEVATED TEMPERATURES," TWENTIETH QUARTERLY REPORT CONTRACT NAS 3-9439, NAS CR-72632, TRW EQUIPMENT LABORATORIES, JULY 7, 1969.

Figure 7-7. Refractory Alloys 1% Creep Properties

7.4 NOBLE METAL ALLOYS

The noble metal alloys were investigated because they exhibit the attractive feature of high temperature stability in both oxidizing and vacuum environments. Ground tests could therefore be conducted in air without requiring a vacuum or inert gas environment, and the problem of evaporation during space operation would be absent.

Data for the pure noble metals (rhodium, iridium and platinum) indicate that their low creep strength would preclude their use for HSA components, hence they were eliminated as candidate materials.

The noble alloys are presently under development and are not nearly as well characterized as the refractory alloys and superalloys, consequently an extensive materials test program to fully evaluate the materials would be required. Further, the cost of these materials is extremely high. Comparisons with the other HSA candidate materials are made in paragraph 7.5.

7.4.1 MECHANICAL PROPERTIES

Mechanical Properties for the Noble metal alloys are given in Table 7-5. Creep data is essentially unavailable for these alloys; however, it is believed that the tungsten alloyed varieties will behave similar to TZM, the arc cast molybemums, or CB 752. As such creep data was derived by normalizing these data to the short term tensile strengths of the related materials. On this basis one would conclude that ternary noble alloys offer a distinct advantage in creep strength over the binary alloy counterparts.

TABLE 7-5. MECHANICAL PROPERTIES OF NOBLE METAL ALLOYS

Metal/Alloy	Density		Melting Point	Tensile Strength		Yield Strength		Coefficient of Expansion		Creep Strength(1)			
										Rupture		1%	
	gm/cm^3	lb/in^3	°K	N/cm^2	Psi	N/cm^2	Psi	10^{-6} cm/cm/°C	10^{-6} in/in/°F	$10^3\ N/cm^2$	KSI	$10^3\ N/cm^2$	KSI
Pt30Rh	17.5	.635	2203	24,100	35,000	17,900	26,000	8.8	4.9	0.69	1.0	0.41	0.6
Pt26Rh8W	17.7	.640	2273	35,800	52,000	26,200	38,000	8.5	4.7	5.85	8.5	0.14	0.2
Pt30Rh10W	18.2	.660	2333	42,600	62,000	29,600	43,000	8.3	4.6	7.03	10.2,	2.2	3.2

(1)Extrapolation of 1255°K-100 Hr Data to 40,000 hours

7.5 TRADEOFFS

7.5.1 Weight, Structural Stability and Cost

Preliminary structural sizing of the candidate Heat Source Heat Exchanger designs was performed to evaluate structural and weight characteristics in the selection of materials. Sizing of the elements is dictated primarily by the one-percent creep strength limits in order to limit distortion changes and control critical dimensions during the five-year mission life (~40,000 hours). Since little data is available for most materials at lifetimes greater than 1000 to 2000 hrs, extrapolations of data were made to estimate the 40,000 hour creep properties.

Table 7-6 summarizes results of the structural evaluation for a spectrum of candidate materials and includes estimated material costs for the HSHX candidate designs. The Table also includes a relative comparison between the materials to resist transient thermal stresses in the HSHX mounting support frames (see Figure 11-2). The thermal stress sensitivity parameter ΔT is indicative of the maximum allowable temperature differential across the support frame assuming an average frame temperature of 866° K (1100° F) and an initial HSA temperature of 644° K (700° F). The analysis is based on elastic strain theory where

$$\Delta T = \frac{\sigma_C - C_O}{E\alpha},$$

the limiting stress σ_C is the critical yield crippling strengths of the frame. C_O is a constant depending on temperature gradient profile, E is Young's Modulus and α is the coefficient of expansion.

The conditions for inducing thermal stress are expected during the launch transient phase subsequent to shutdown of pad cooling and prior to reaching operating stabilization temperatures. Preliminary estimates indicate that a ΔT across the support frame of between 250° K and 300° K (450° F and 550° F) is to be expected during the

TABLE 7-6. MATERIAL DESIGN TRADE-OFF CHARACTERISTICS

Material	Support Frame Thermal Stress Sensitivity** ΔT Max °K (° F)	HSHX Wall Gage cm (in.) Axial Tube Bank	HSHX Wall Gage cm (in.) Plate Fin	HSHX Weight kg (lbs) Tube	HSHX Weight kg (lbs) Fin	Material Costs ($) Tube	Material Costs ($) Fin
Refractory Alloys							
Ta-10W	251 (470)	.051 (.020)*	.142 (.056)	19 (42)	22.2 (49)		
T-111	294 (530)	.051 (.020)*	.142 (.056)	19 (42)	22.2 (49)	8,400	9,800
Cb-129Y	344 (620)	.051 (.020)*	.223 (.088)	12.7 (28)	14.0 (31)	5,000	5,500
Cb-103	344 (620)	.051 (.020)	.274 (.108)	12.7 (28)	18.1 (40)	5,000	7,300
Cb-1Zr	400 (720)	.051 (.020)	.274 (.108)	12.2 (27)	17.7 (39)	5,000	5,000
Noble Alloys							
Pt 30 Rh	300 (540)	.127 (.050)	.635 (.250)	53.5 (118)	95.0 (210)	354,000	629,000
Pt26Rh8W	316 (570)	.051 (.020)*	.228 (.090)	24.4 (54)	27.2 (60)	162,000	181,000
Pt30Rh10W	322 (580)	.051 (.020)*	.205 (.081)	25.0 (55)	28.6 (63)	164,000	188,000
Superalloys							
HA-188	150 (270)	.101 (.040)	.535 (.210)	22.6 (50)	41.6 (92)	650	1,200
TD-NI	172 (310)	.064 (.025)	.366 (.144)	13.1 (29)	24.0 (53)	1,300	2,400

*These dimensions established by fabrication limits rather than creep strength requirements.
**Support frame temperature - 866°K (1100° F).

launch transient; comparison of the values in the table to the predicted ΔT determines whether design requirements are met.

The following observations are made from Table 7-6.

1. The thermal stress capability for superalloys is less than the estimated ΔT, indicating a marginal design.
2. The required gages for a plate fin HSHX, fabricated from superalloys are large, and probably border on, reasonable limits for fabrication.
3. The material costs for the noble metal alloys are extremely high.
4. The columbium alloys result in the lowest weight system and, in general, produce the greatest margin with regard to thermal stress.

From the above the following conclusions are reached:

1. Noble metal alloys are not a viable candidate material because of excessive cost.
2. Superalloys are not considered to be an attractive candidate because their structural properties (high coefficient of expansion, low creep strength) at high temperatures result in a marginal HSA design and a coating would probably be required to prevent high evaporation loss in vacuum.
3. The columbium alloys are preferred over tantalum alloys because of their lower weight. Although the tantalum base alloys exhibit greater creep strength than the columbium alloys, their higher densities and lower ductility offset this advantage, especially since the columbium alloys exhibit sufficient strength for the HSA design.

From the above considerations, columbium refractory alloys are recommended for fabrication of the HSHX and other HSA components within the insulation enclosure.

7.5.2 FABRICABILITY AND COATABILITY

Selection of a particular columbium alloy is based on the ease of fabricating and coating. Coatability is included because of the desirability to increase the emissivity of the HSHX to minimize Heat Source operational temperatures. The columbium alloys exhibit emissivities that are less than 0.3. Fabricability is assessed by the ability to work and weld the material.

Cb-129Y is difficult to weld. Cb-1Zr is readily worked and welded. It can be coated or grit blasted to increase its emissivity. Cb-103 can also be easily worked and welded. It can be coated a little more readily than Cb-1Zr, and can also be grit blasted to increase the emissivity. Both Cb-1Zr and Cb-103 satisfy all the requirements of paragraph 7.1.1 and remain as viable candidates. Further material characterization at HSA operational temperatures for both materials, however, is required before final selection can be made.

7.6 COMPATIBILITY OF COLUMBIUM ALLOYS

1. Reaction with Gases

   Like other electropositive elements and their alloys, columbium alloys react with gases such as oxygen, nitrogen, carbon oxides, and water vapor.

   a. Oxygen enters the metal interstitially and goes into solid solutions. It combines with trace elements which precipitate in grain boundaries as oxides. This results in embrittlement and hardening of the alloy along with an associated decrease in ductile brittle transition temperature (DBT).

   b. Columbium and its alloys dissolve nitrogen starting at temperatures in the range of 1323°K. Its solid solubility is the highest for pure columbium and decreases as the concentration of alloying elements such as tungsten, molybdenum, hafnium, etc., is increased. The presence of nitrogen lowers oxidation resistance and lowers DBT due to the formation of nitrides in grain boundaries.

   c. Water vapor reacts with columbium and its alloys at temperature as low as 1373°K (2012°F). The products of reaction degrade alloy properties by inducing intercrystalline boundary buildup of oxide precipitates and the introduction of hydrogen in the crystal lattice, resulting in embrittlement.

   From the above considerations it is evident that the HSA, fabricated from the recommended columbium alloys cannot be brought to operating temperatures in an air environment.

2. Stability of Columbium Alloys in Contact with Graphite

   The carbides of elements in columbium alloys form at slow rates, at temperatures in the range of 1473°K to 1873°K (2192°F to 2912°F) in the presence of hydrocarbon gases and when in contact with carbon. At 2273°K (3632°F) reactions proceed at rapid rates taking only hours to complete. As carbon diffuses into the metal in small quantities, carbide embrittlement results. Therefore, it is necessary to prevent columbium alloys from contacting graphite at high temperatures. For the HSA design, columbium will not contact the Heat Source graphite emissivity sleeve during high temperatures operation, hence no compatibility problem with graphite is anticipated.

3. Other Compatibility Considerations

   No adverse reactions with the working fluid, helium-xenon, or as a result of the nuclear radiation from the isotope have been identified. It will be necessary to confirm the compatibility of refractory alloy manifolds with the Mini-Brayton BRU and recuperator interfacing materials.

7.7 MATERIAL RECOMMENDATIONS

On the basis of the foregoing discussions, the material recommended for the HSHX and other HSA high temperature components is either of the refractory columbium alloys, Cb-103 or Cb-1Zr. The HSA can be designed with adequate margins of safety and fabricated from these materials into reliable hardware for a five-year operational lifetime in space. Some additional long time creep property data at HSA operating temperature must be developed to perform detail design analyses. Mini-Brayton ground system tests at power must be conducted with the HSA either in a vacuum chamber or in an inert gas environment to prevent oxidation of the refractory alloy.

SECTION 8

HEAT SOURCE HEAT EXCHANGER (HSHX)

The Heat Source Heat Exchanger is the component which transfers the thermal energy from the Heat Source to the gas stream. In normal operation, it operates at a temperature intermediate between the Heat Source surface and the working fluid. This section deals with the concepts which were initially screened, the performance of the several concepts which survived initial screening, the stress analysis which affected the selection process, and the final trade off and assessment process.

8.1 CONCEPTS

During the study, five potential HSHX concepts were identified as shown in Figure 8-1.

Concept A consists of a tube spirally wrapped around the Heat Source. It is a simple concept with a minimum of joints and no flow distribution problems. However, the pressure drop in a single tube is excessive.

Concept B consists of axial headers which are connected with semi-circular tubes. It proved to have both acceptable heat transfer and pressure drop with 0.635 cm (0.25in) OD tubes, but not with 1.27 cm (0.5 inch) OD tubes. In addition to being sensitive to tube sizing, it appeared that shaped headers would be required to prevent flow maldistribution, and that many joints would be necessary.

Concept C consists of axial tubes fastened to annular headers. Although a large number of joints are required, both heat transfer and pressure drop were entirely acceptable. Flow distribution would be easier to control than Concept B since the tubes were longer and the headers would be in an area of the HSA where more room was available.

Concept D consists of two large concentric cyclinders with corrugated sheet metal between them. Both heat transfer and pressure drop were acceptable, however, questions of the stress developed in the large diameter tubes, and fabrication of the entire unit required resolution. A variation of Concept D involves forming fins by machining axial grooves in the inner cyclinder and bonding the outer cyclinder to the

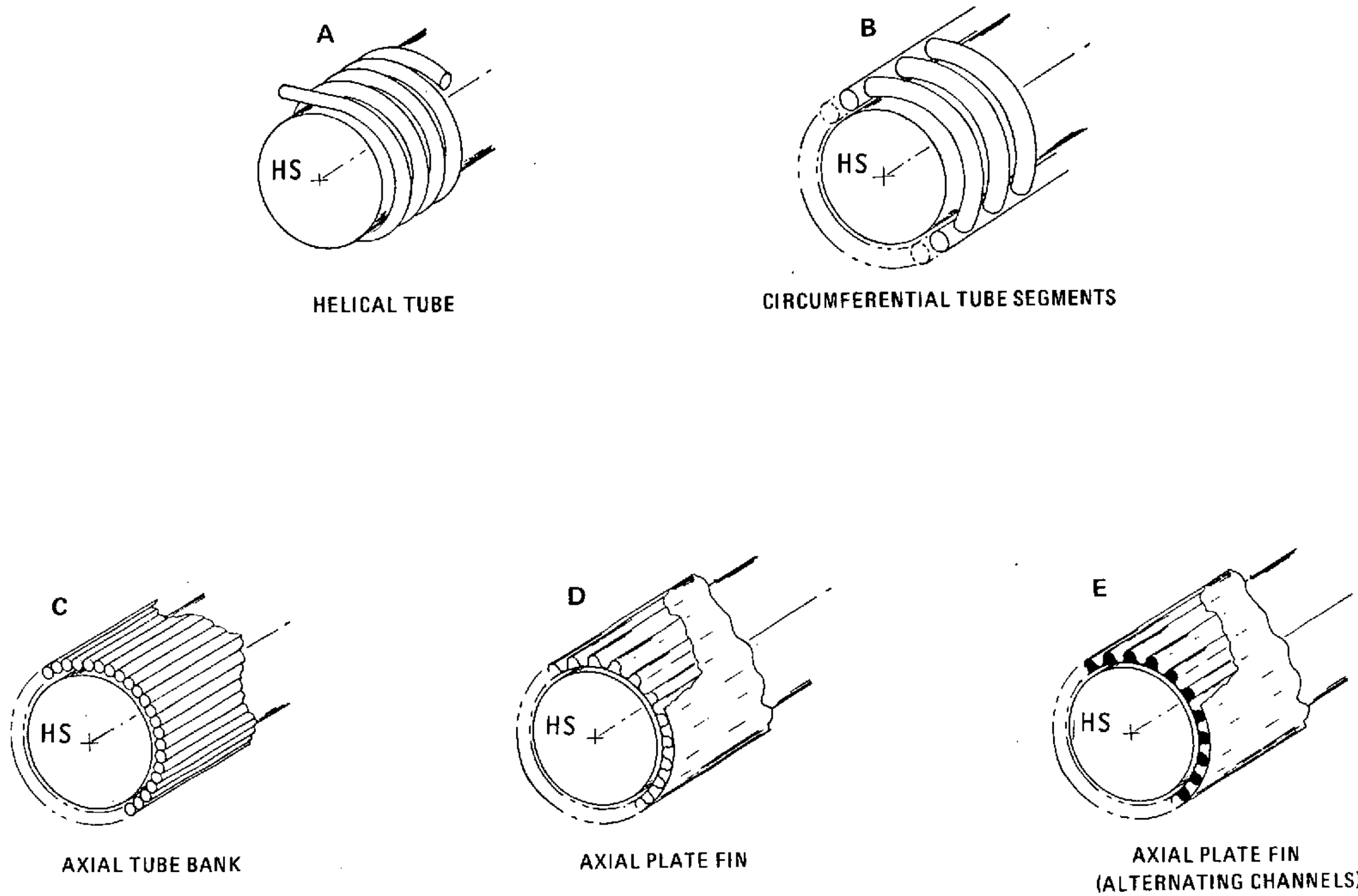


Figure 8-1. Heat Source Heat Exchanger Concepts

tips of the fins by diffusion welding. Its heat transfer and pressure drop characteristics are similar to D. This concept seemed to eliminate the questionable characteristics of corrugated plate fin concept.

The last concept, E, was similar to Concept D, except that alternate channels were to be used for the auxiliary cooling system. It appeared that the manifolds (headers) would be very complex.

Selection of viable HSHX designs are based on acceptable pressure drop, heat transfer characteristics, stress response and fabricability. An initial screening of the concepts-summarized in Figure 8-2 - eliminated all but the axial tube bank (Concept C) and plate fin HSHX's (Concept D). The other concepts, excluded from further considerations, exhibit either unacceptable pressure drop characteristics or complex manifolding and ducting.

8.2 THERMAL/HYDRAULIC PERFORMANCE

Figures 8-3 and 8-4 show the thermal/hydraulic performance of the tube and plate fin concepts selected as a result of the initial screening process. Figure 8-3 is for the axial tube configuration in which the significant variables are for the low pressure system case (which is the limiting one). It shows the core pressure drop, number of tubes, and the maximum Heat Source temperature which is required to remove 2400 watts from the heat source across a vacuum gap. Two cases are shown, one for a solid wall of tubes (the solid lines) and another for tubes spaced one diameter apart (the dashed lines). The Δ P limit shown is a sufficiently large fraction of the total ΔP limit (0.149N/cm^2 or 0.216 psi) so that flow distribution can be controlled without either orifices or shaped headers. The temperatures are given for a high HSHX emissivity coating ($\epsilon = 0.8$) which might require a coating development program to obtain. The baseline design however, assumes an emissivity of $\epsilon = 0.4$ which is considered within the present state of the art and which would result in temperatures approximately 22°K (40°F) above those shown on the figures.

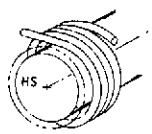
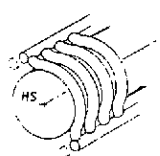
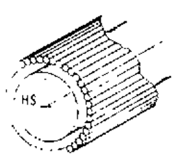
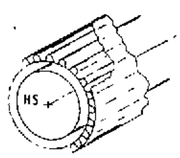
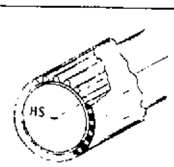
CONFIGURATION	PRESSURE DROP	HEAT TRANSFER CAPABILITY	STRESS	FABRICABILITY	COMMENTS
 HELICAL TUBE	EXCESSIVE	ACCEPTABLE WITH SMALL TUBES	GOOD	GOOD	ELIMINATED AS A CANDIDATE
 CIRCUMFERENTIAL TUBE SEGMENTS	0.029 N/CM^2 (1/4 INCH TUBES)	ACCEPTABLE WITH 1/4 INCH OD TUBES NOT ACCEPTABLE WITH 1/2 INCH OD TUBES	GOOD	FAIR	MAY NEED SHAPED AXIAL DUCTS. ELIMINATED AS A CANDIDATE
 AXIAL TUBE BANK	0.018 N/CM^2 (1/4 INCH TUBES)	ACCEPTABLE	GOOD	GOOD	STRAIGHT-FORWARD DESIGN, MANY JOINTS
 AXIAL PLATE FIN	ACCEPTABLE	ACCEPTABLE	FAIR	GOOD	NEEDS HEAVYWALLS FOR HIGH PRESSURE SYSTEM. FEWER JOINTS THAN AXIAL TUBE BANK HSHX
 AXIAL PLATE FIN (ALTERNATING CHANNELS)	ACCEPTABLE	ACCEPTABLE	POOR	POOR	MANIFOLDS ARE VERY DIFFICULT, ELIMINATED AS A CANDIDATE

Figure 8-2. HSHX Trade-Offs

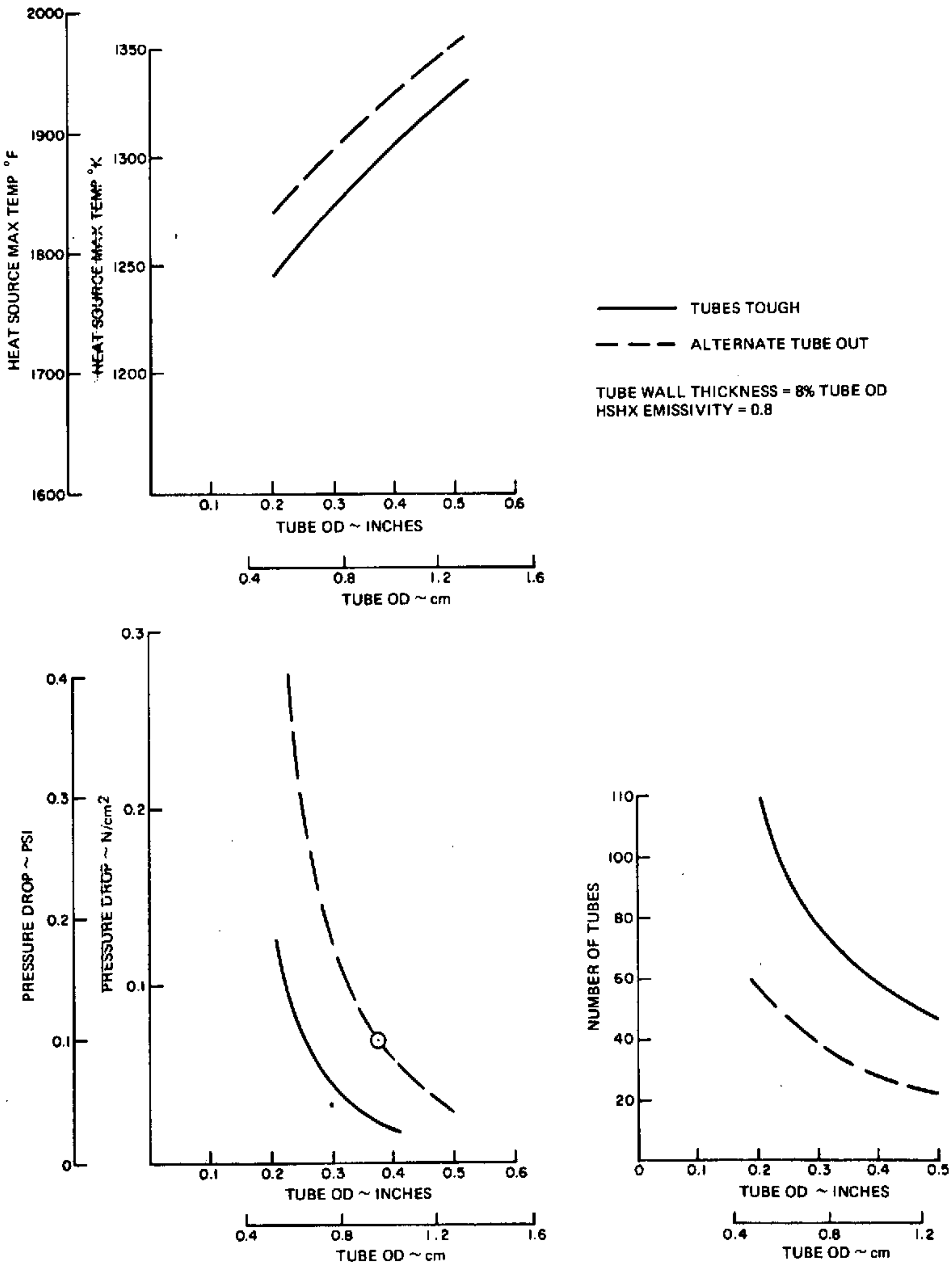


Figure 8-3. Tubular HSHX Thermal/Hydraulic Performance

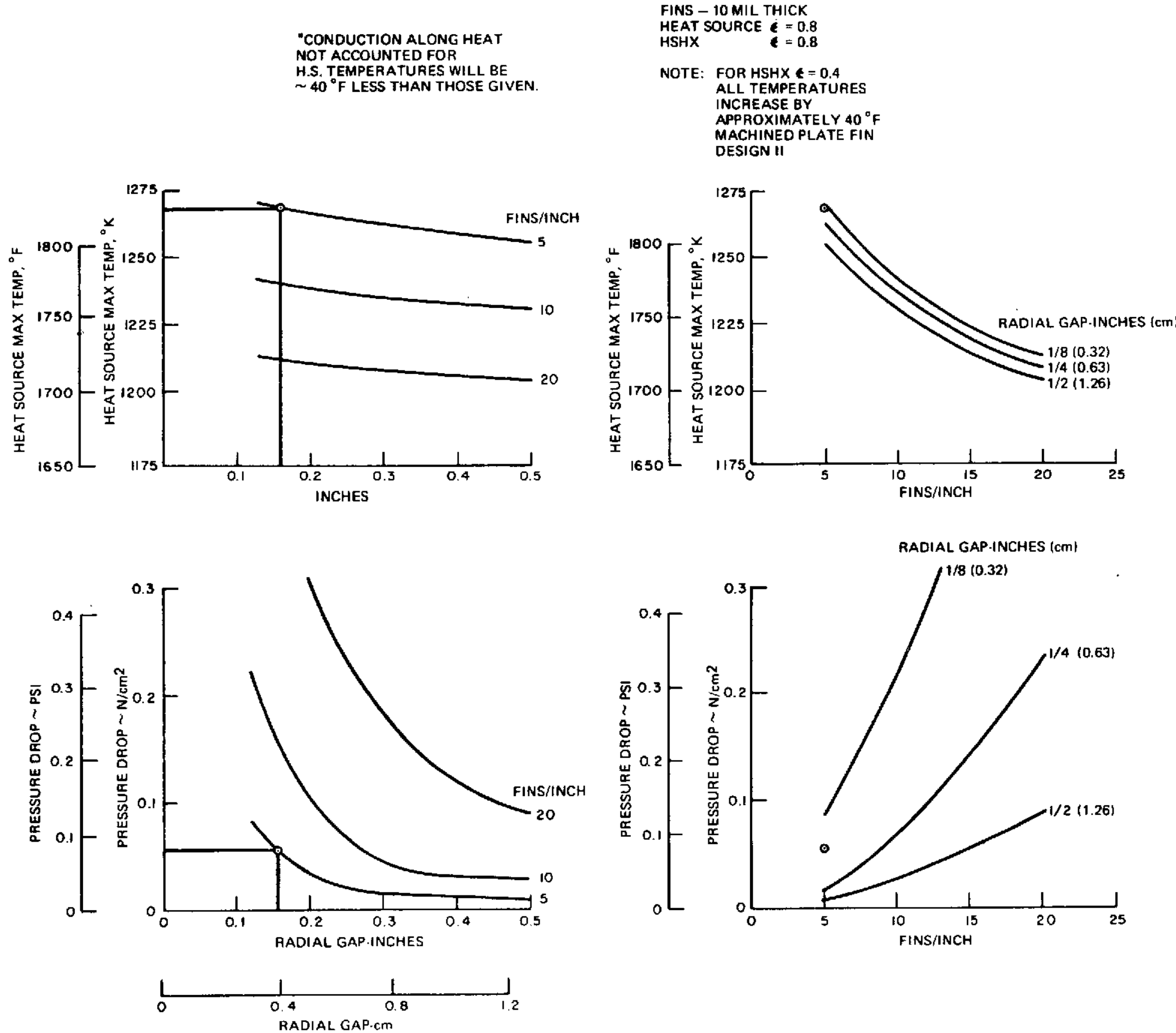


Figure 8-4. Plate Fin HSHX Thermal/Hydraulic Performance

Figure 8-4 shows similar details for the fin type heat exchanger. The variables here are fin spacing, fins per inch and fin thickness, typically 0.025 cm for the corrugated fin and 0.051 cm or greater for the machined fin concept. This figure and Figure 8-2 agree quite well, as can be seen by converting a machined fin case (5 fins/inch, 0.051 cm thick, 0.406 cm wide annulus) to an equivalent tubular design. There are about 125 channels in this design and they are touching. They are thermally similar to the case of 125, 0.508 cm OD tubes. The pressure drop is lower for the finned design, however, due to the total area difference as well as the channel shapes.

Manifolding between parallel units (one to three units) and within the HSA was also considered. Figure 8-5 shows the arrangement considered for the tube-header design, Concept C. Manifolding would be similar for the plate fin designs. Table 8-1 shows the pressure drops associated with the low pressure (1 unit) and high pressure (3 units) system for a 90 tube HSHX design. Note that the one unit, low pressure system is limiting, and that a slightly larger manifold transition pipes would be required for this particular design to reduce the total ΔP slightly.

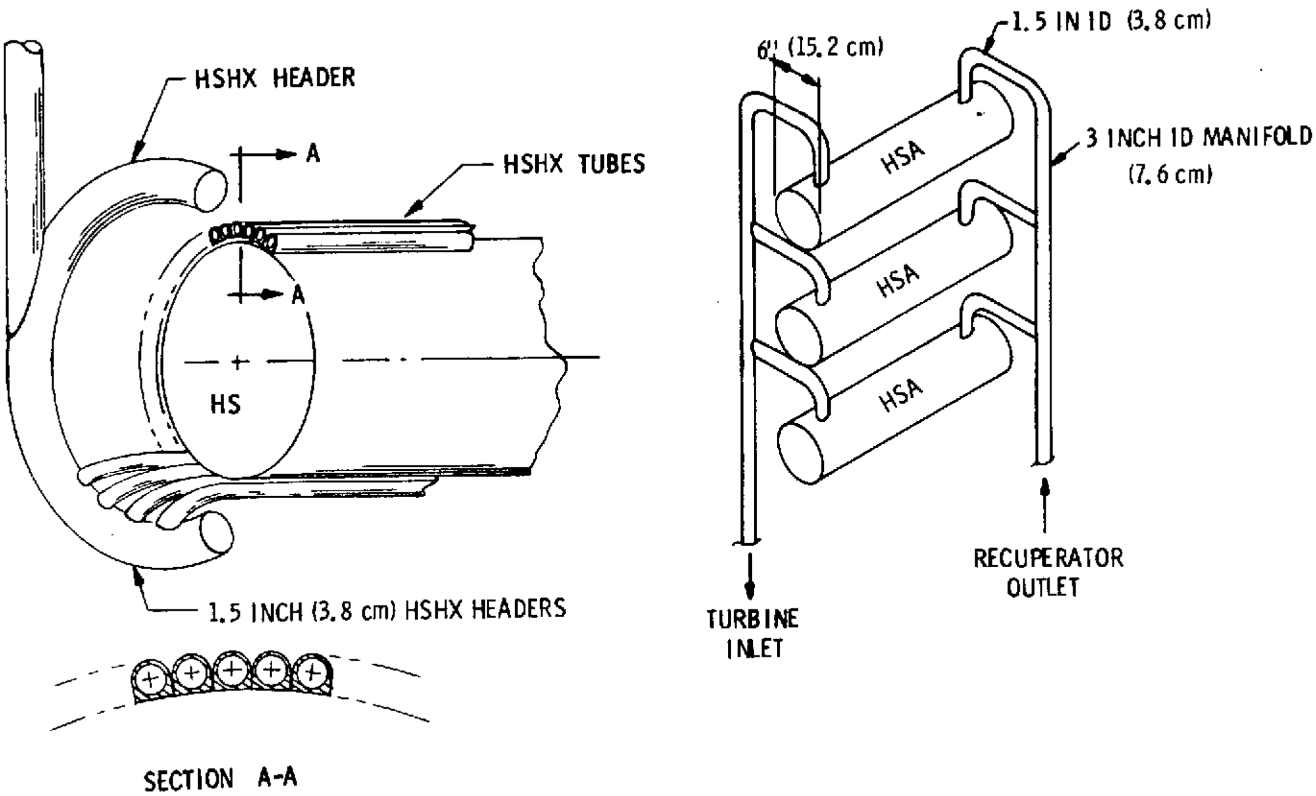


Figure 8-5. Headers and Manifolding Concepts

TABLE 8-1. PRESSURE DROP ANALYSIS
CONCEPT C - AXIAL TUBES

Item	Size	3 HSA's Pressure Drop (high pressure) N/cm^2	3 HSA's Pressure Drop (high pressure) psi	1 HSA Pressure Drop (low pressure) N/cm^2	1 HSA Pressure Drop (low pressure) psi
HSHX Tubes	90 Tubes; 0.0635 CM ID (1/4 in.)	0.021	0.031	0.063	0.091
Bend Into HSHX Header (2)	90 Degree Bend	0.015	0.022	0.046	0.066
Expansion Into HSHX Header	-	0.006	0.008	0.016	0.024
Header (including exit)	3.8 CM ID (1.5 in.)	0.002	0.003	0.006	0.009
Header-Manifold Transition Pipe (includes 90° bend)	3.8 CM ID x 15.3 CM Long (1.5 in. ID x 6 in. long)	0.019	0.028	0.021	0.031
Inlet and Outlet Manifold Piping (For 3 Units)	7.6 CM ID x 61 CM Long (each) (3 in. ID x 2 ft. long)	0.002	0.003	-	-
	Total ΔP	0.065	0.095	0.152	0.221
	Allowable ΔP	0.157	0.228	0.149	0.216

8.3 STRESS ANALYSIS

The preliminary stress analysis was directed at general sizing of tubes and plates for the various designs. Three areas were studied in some detail.

The tubes in the axial tube designs are limited by the creep stress due to the high-pressure operating requirement. For the small diameter tubes (0.635 cm to 1.27 cm or 0.25 to 0.5 inch) required thickness ranged from 0.015 cm (0.006 in) with tantalum based refractories to .015 cm (.02 inch) with columbium alloys in the 0.635 cm (0.25 inch) tube size, which appeared unlikely to cause fabrication problems.

The headers in the axial tube design, where the small tubes enter a flat ring, presented a different problem. Calculations showed that thickness ranging between 0.36 cm (0.14 in) for tantalum alloys to 0.79 cm (0.31 inch) with columbium alloys, would be required. As later fabrication studies showed, the interface between the small gauge tube and these thick sections posed a serious, but not unsurmountable problem.

The concentric cylinders forming the flow channels in the plate-fin concepts were also creep limited. Several assumptions led to this conclusion. With the corrugated plate-fin, the bonding between the thin fin material and the concentric cylinders would have to be excellent to provide any support, and it appeared that if the fins restrained the cylinders, the fins could be deformed or broken by the creep forces. If the fins were not well bonded to the outer cylinder (not required by heat transfer considerations) they would not restrain its deformation. Therefore, the cylinders were analyzed as unsupported with respect to radial creep. For flow gap of up to 1.27 cm (0.5 inch), wall thicknesses ranged from 0.114 cm (0.045 in) for tantalum alloys to 0.254 cm (0.10 in) for columbium alloys. No fabrication problems are anticipated for these gauges.

8.4 TRADEOFFS

The tube design results in the lightest weight HSHX (see Section 11) but requires many more parts and welded or brazed joints, than the plate fin. As discussed in Section 12, fabrication of a refractory corrugated plate fin HSHX is difficult because of long blind braze joints at the corrugation/cylinder wall interface. The machined plate fin HSHX does not exhibit this problem since it can be assembled with diffusion bonds between the fin and the outer cylinder wall to form a monolithic structure. From this point of view it appears to be the best design. Nonetheless, all three HSHX concepts (tube, corrugated plate fin and machined plate fin) are considered acceptable.

SECTION 9

AUXILIARY COOLING SUBSYSTEM

The Auxiliary Cooling System is an active system designed to cool the heat source when the Brayton Rotating Unit is not operating. It provides the ability to load the HS into the HSA without starting the unit until orbit is achieved.

9.1 <u>REQUIREMENTS</u>

The ACS must maintain exposed surfaces of the HSA to temperatures not exceeding 466.5°K (380°F) and must limit the graphite surface of the Heat Source to temperature below 500°K (440° F) in the presence of an oxidizing environment.

9.2 CONCEPTS

Figure 9-1 shows seven concepts considered for active auxiliary cooling of the HSA. An inherent requirement is that the ACS design be capable of being integrated with the HSHX.

Concept A is a simple helical tube wrapped around the outside of the HSHX. Because of the thermal resistance represented by the HSHX, the coolant flow can not maintain the Heat Source at its requisite temperature of 672° K (750° F) on the pad. If the helical tube is located inboard of the HSHX it impedes heat transfer from the Heat Source to the HSHX during Mini-Brayton power operation. Consequently this concept was eliminated as a candidate.

Concept B consists of circumferential tube segments with axial headers. It would be difficult to integrate this design with the HSHX axial tube and plate fin configurations and in addition it has the same heat transfer problem described above for concept A. This concept therefore, was also eliminated as a candidate.

Concept C provides cooling flow outside the thermal insulation. Although it can maintain exposed surfaces below 466.5°K (380°F) it will not satisfy the second requirement of maintaining the Heat Source surface temperature below ~500° K (440° F). This concept was eliminated as a candidate.

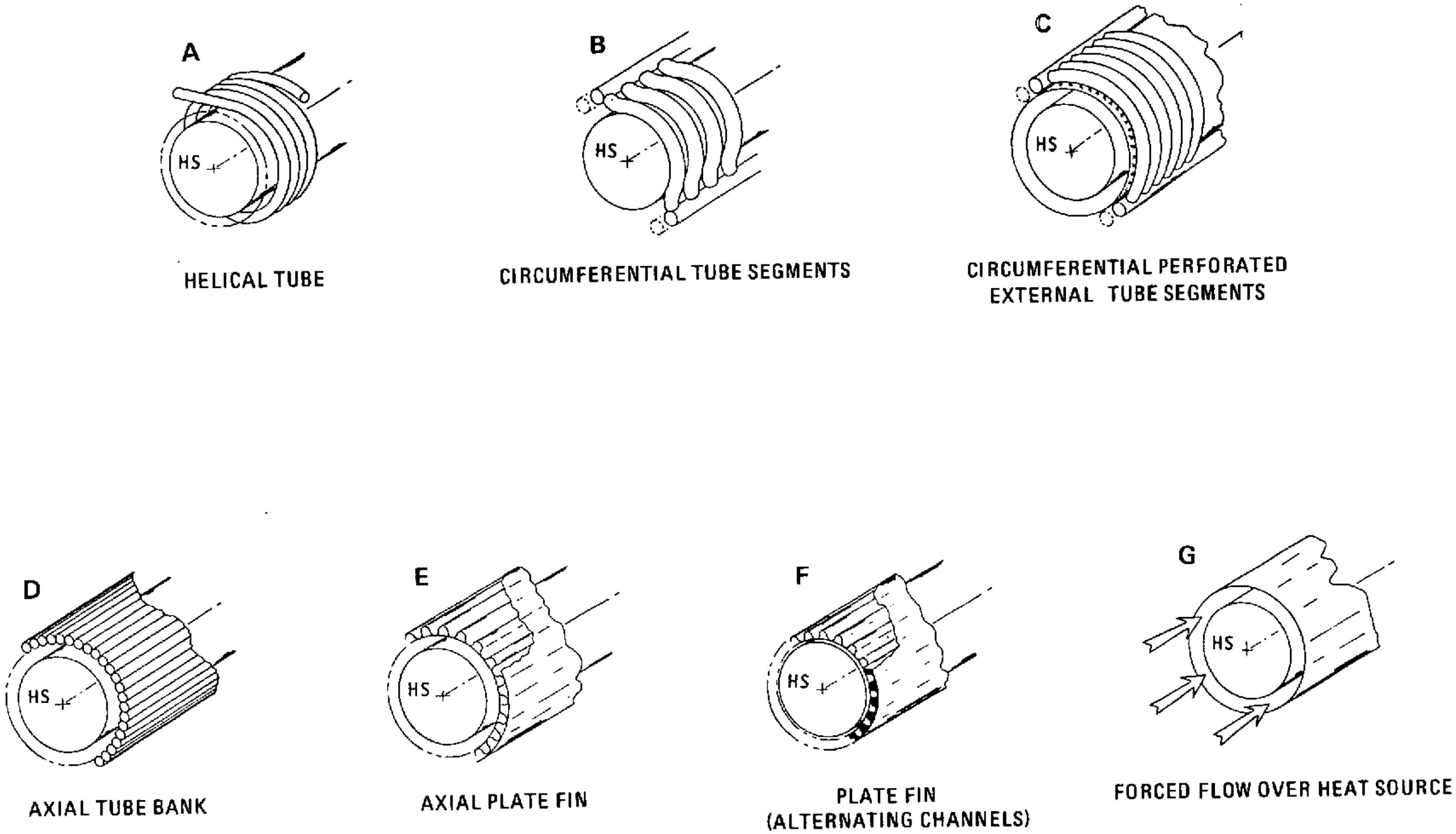


Figure 9-1. Auxiliary Cooling Subsystem Concepts

Concepts D and E are an axial tube bank and plate fin configuration respectively, similar to the HSHX concepts discussed in the previous section. A design in which either of these Auxiliary Cooling Heat Exchangers is entirely inboard or outboard of the HSHX is unacceptable from a heat transfer point of view as discussed for concept A. The only configuration which would meet design requirements are axial tubes that alternates with an axial HSHX tubes. Although this alternating tube configuration is a feasible concept it has not been selected as the prime candidate for the reasons discussed in the next paragraph where the selected concept is described.

Concept F which provides alternate cooling and HSHX channels in a plate fin configuration, results in complex manifolding and was consequently eliminated.

Concept G is quite different from the others which confine the cooling flow to passages in the same manner as the HSHX. In this concept the cooling flow is ducted directly over the Heat Source in the annulus formed by the outer surface of the Heat Source and the HSHX inboard wall. Since the Heat Source is cooled directly by convection it is apparent that this is the most thermally efficient auxiliary cooling system. It is also the lightest in weight since it utilizes an existing annulus and requires the least amount of additional hardware. It consequently is the selected approach. Typical auxiliary cooling flow requirements for three gases at 294° K (70° F) which are potential coolants, are given in Table 9-1.

TABLE 9-1. AUXILIARY COOLING REQUIREMENTS

	Annulus Gap		
	0.318 cm (0.125 in)	0.635 cm (0.25 in)	
Maximum HS Temperature °K (° F)	672° (750°)	672° (750°)	450° (350°)
Helium Flow Rate - Kgm/hr (lb/hr)	4.9 (10.8)	—	32 (70)
Nitrogen Flow Rate - Kgm/hr (lb/hr)	57.2 (126)	81.6 (180)	236 (520)
Argon Flow Rate - Kgm/hr (lb/hr)	—	—	526 (1160)

9.3 OPERATIONAL OPTIONS

A number of options are possible in operating the ACS. The ACS can be used with an inert gas of high purity to provide a cover gas over the Heat Source should it be desirable to operate the Mini-Brayton system at power on the launch pad. Additionally, if it is at all necessary to provide cooling within the shuttle payload bay either during ascent, during parking orbit periods or during re-entry (if the complete HSA or Mini-Brayton system is retrieved), a cooling gas supply can be provided as ancillary equipment in the shuttle and connected to the ACS inlet port. For such operation, the coolant would either vent to the payload bay or overboard to space using appropriate ducting. Similarly upon landing, either a ground cooling gas supply can be provided for the ACS (as it is on the launch pad), or coolant can be carried along in the shuttle in the event of a possibility of landing at a remote site. The latter contingency should probably be planned for as a safety precaution.

SECTION 10

EMERGENCY COOLING

The Emergency Cooling Subsystem provides passive cooling of the Heat Source in the event of any operational failure of the Mini-Brayton Power Conversion system or HSA, which produces an overtemperature of the Heat Source after lift off.

10.1 REQUIREMENTS

The ECS is designed to the following requirements

1. It must operate only once.
2. It must be capable of operating with high reliability over the 5 year operational life time.
3. It should not rely on any external power for generation of an electrical signal.
4. It must limit the external surface (emissivity sleeve) of the Heat Source to steady state temperatures not exceeding 1373° K (2012° F).
5. It must limit peak transient temperatures on the PICS fuel/Iridium interface to less than 2372°K (3810°F) for a maximum of five (5) minutes. The corresponding Heat Source surface temperature is estimated to be 1922° K (3000° F).

10.2 CONCEPTS

The Emergency Cooling Subsystem consists of two insulated end doors, activated by an Emergency Cooling Device which responds to overtemperature of the Heat Source. The forward door also serves as the Heat Source loading door. The steady state temperature distribution along the Heat Source that results with both doors open in space is given in Figure 10-1. A heat sink temperature of 339° K (150° F) was assumed. The maximum HS surface temperature of 1167° K (1640° F) occurs at the mid point along the Heat Source. The temperature at the radiating ends of the Heat Source is 853° K (1076° F). These temperatures are well below the operating temperature of the Heat Source in the Mini-Brayton System. During the time to reach steady state conditions the transient temperatures will also be lower than operational temperatures.

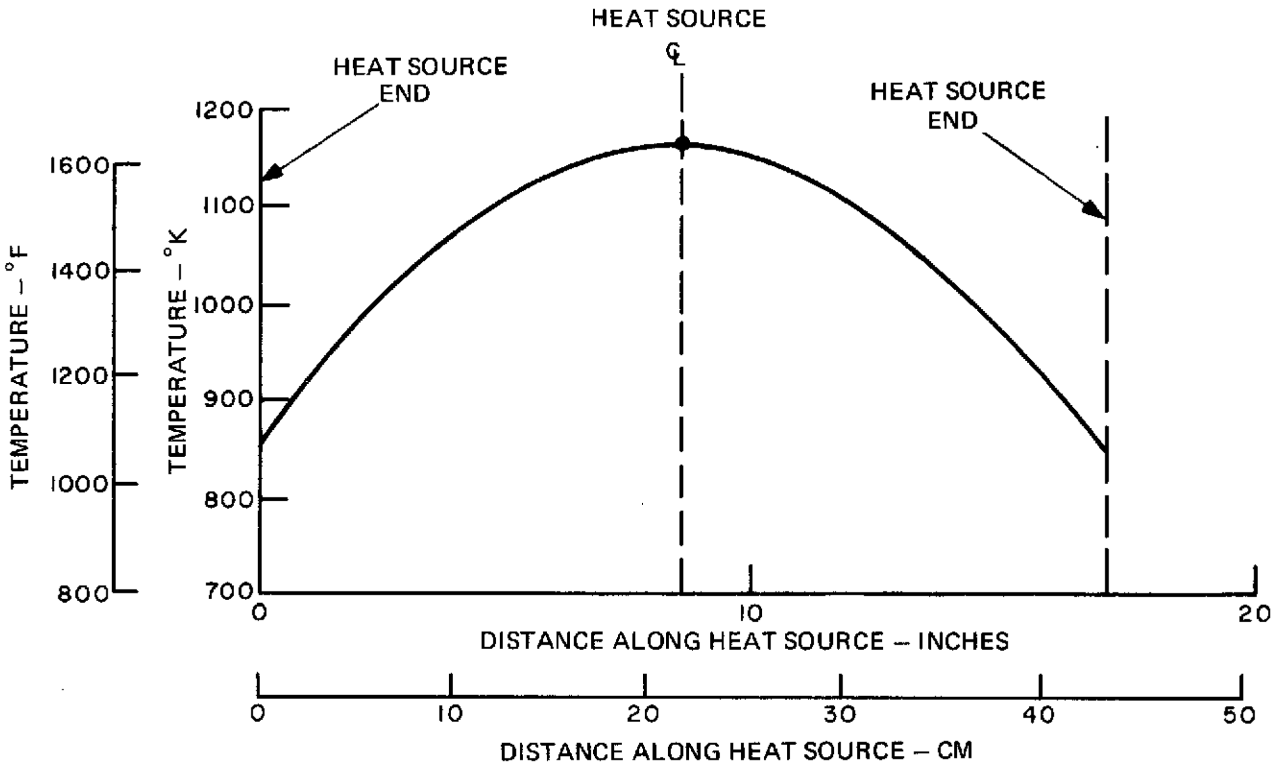


Figure 10-1. Heat Source Surface Temperature with Emergency Cooling Doors Open.

With only one end door open a large temperature gradient and an excessively high temperature at the end of the Heat Source opposite the open door, occur. Although the radiating surface would be 1032° K (1398° F), the heat Source temperature at the opposite end would exceed 3100° K (5120° F) which is beyond safe levels. This imposes the requirement that for emergency cooling, both doors must open.

The device that responds to a Heat Source overtemperature and opens the doors is the Emergency Cooling Device. Four types of temperature response mechanisms considered are as follows:

1. Gas or liquid expansion
2. Expansion of a mechanical link
3. Melting of a mechanical link (fusible link)
4. Pyrotechnic devices (pyrotechnics which activate by an electrical impulse would violate requirement 3 of paragraph 10.1).

A fifth concept is discussed which violates requirement 3 of paragraph, 10. 1, since it relies on generation of an electrical signal. It is presented because it represents a simple and reliable device which may justify re-examination and perhaps relaxation of that design requirement.

The concepts are depicted in Figure 10-2. All of the ECD's disengage a spring loaded release and latch mechanism on each of the two end doors; a spring loaded door hinge diametrically opposite the latch release, forces each door to a full open position. The door hinge would be provided with a manual release (not shown on the figure) for opening the doors during assembly Heat Source loading and to provide a contingency for removing the Heat Source from the shuttle in the event of an emergency on the pad. The springs are all located in a low temperature region outside the HSA insulation blanket, to avoid potential high temperature creep problems. No attempt has been made to optimize or even design the latch and hinge. They are shown as a simple working concepts to illustrate the functional operation of the ECD. It is possible for example to combine the latch release mechanism and the door hinge into one assembly so that in all modes the doors rotate about one axis.

Configuration "A" is an example of a liquid/gas expansion device. A container of either liquid or gas responds to the temperature rise of the heat source with a rise in pressure. At a pressure corresponding to the abnormal temperature, a prestressed membrane (rupture disk) releases the stored energy driving a piston connected to the latch release mechanism, allowing the doors to open.

Configuration "B" is an example of a thermal expansion device. A metal strap with a predicatable rate of expansion grows in length as the heat source temperature rises above normal. When the heat source reaches a critical temperature, the metal strap has grown to a length that initiates the release of the spring loaded rod in the latch release.

In Configuration "C" a retaining link in the latch release assembly is melted, releasing a spring loaded pin which in turn activates the latch release mechanism. Melting of the retaining link occurs as a result of direct conduction along a thermal conductive

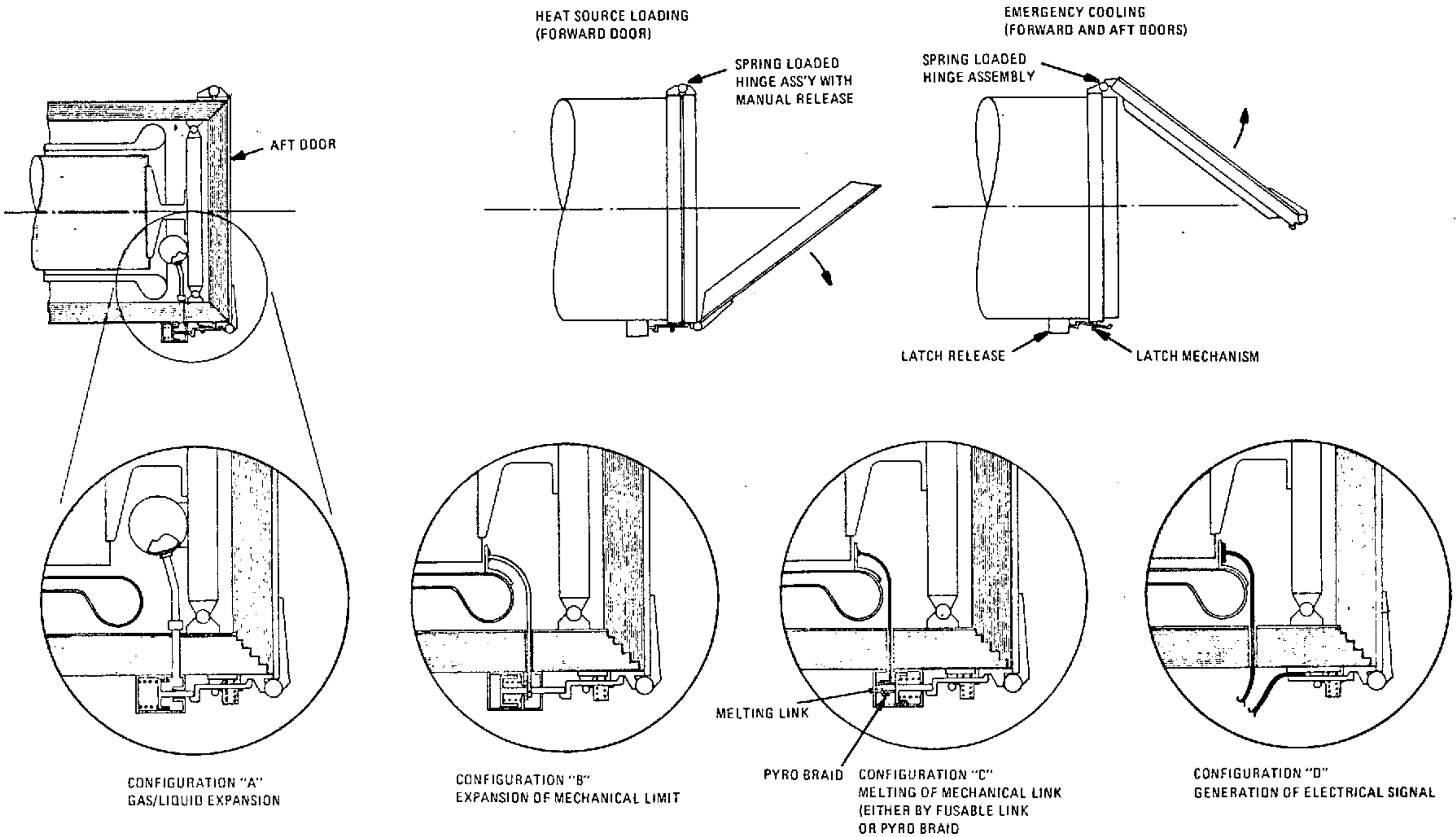


Figure 10-2. Emergency Cooling Device Concepts

strap or by ignition of a pyrotechnic braid which in turn melts the retaining link. This ECD can be designed so that the melting retaining link is at the Heat Source Interface, thus not depending on a conductive path.

Configuration "D" employs an electrical signal which initiates the release mechanism. In this concept a thermocouple senses the temperature of the heat source and triggers an electrical impulse to a pyro-assembly restraining the release mechanism. A solenoid can be substituted for the pyro-assembly. A variation of this concept is one that responds to a Mini-Brayton power system failure. A sudden decrease in power is sensed, tripping a relay which initiates the pyro. A small battery on constant trickle charge, floating off the electrical power line, provides the current to fire the pyro. This concept would require an interlock to prevent activation of the device prior to, and during start up of the Mini-Brayton system in orbit.

In each of the above concepts, the ECD activates both doors and is located at the aft end of the HSA, that is, at the end opposite the loading door. The ECD is thermally coupled to the end of the Heat Source either by radiation exchange or by a short conductive strap, so that it responds quickly to any increase in Heat Source temperature. Analyses indicates that the ECD must be located in a region of the HSA that responds quickly to Heat Source temperature. It was found for example that if the ECD is coupled to the structural support container, the temperature response would be entirely too slow; the Heat Source will in this case rise to untolerable levels before the ECD is activated.

10.3 TRADEOFFS

Advantages and disadvantages of each of the concepts are summarized in Table 10-1. On the basis of this preliminary study it would appear that the liquid or gas expansion device may be one of the most attractive concepts since its operation is simple and predictable and the possibility of a leak in the pressure vessel can be minimized by over design. The electrical signal device is probably the simplest and can be designed to assure high reliability. It is recommended that this device be considered. Clearly, however, detailed transient analyses are required before any final ECD concept can be selected. Redundancies for the selected ECD will have to be built into the design to assure very high reliability for operation over the five year life time.

TABLE 10-1. ECD TRADE OFFS

Concept	Advantages	Disadvantages
Liquid or Gas Expansion	Predictable response (increase in pressure) as a function of temperature	Pressure vessel at high temperature for 5 years must not develop leaks
Melting Fusible Link	Simple mechanical device based on an irreversible physical phenomenon	Predictability uncertain. Difficult to select precise temperature for ECD operation since device may release door prior to actual melting as it loses strength and creeps with increasing temperature
Pyrotechnic	Predictable response. Pyro can be selected to fire at desired temp.	Stability of pyro characteristics after 5 years at high temperature uncertain; presence of pyro in isotope system may present potential hazard.
Expansion of Mechanical Link	Predictable response based on expansion characteristics of metal	Creep at high temperature after long time periods may activate doors prematurely
Electrical Signal	Precise, predictable response based on temperature sensor	Requires power for generation of electrical signal.

SECTION 11

HEAT SOURCE ASSEMBLY DESIGN

HSA designs were developed for each of the candidate HSHX designs discussed in Section 8. These are:

1. Corrugated plate fin
2. Machined plate fin
3. Axial tube bank

In the following discussions the HSA designs will be referred to by the above terminology to distinguish them from each other.

11.1 PLATE FIN HSA CONCEPTS

11.1.1 CONFIGURATIONS

Details of the two plate fin Heat Source heat exchanger designs are shown in Figure 11-1. Except where noted structural sizing is based on 1% creep stress limits in the longitudinal directions and 2% in the radial direction. The HSHX wall gauges are sized for 80 N/cm^2 (115 psi) which is the highest Mini-Brayton system pressure. In sizing the HSHX walls no credit is taken for the support constraint provided by bonded fins or corrugations to the outer HSHX cylindrical wall. The HSHX consists of flow channels running axially between two concentric cylindrical walls 0.254 cm (0.10 inches) thick. The differences between the two plate fin HSA's is shown in section AA of the figure. The Machined Plate Fin consists of 0.051 cm (0.02 inch) fins to the inch (~2 fins/cm) and the annulus gap is 0.41 (0.16 inches). The fin dimension and number of fins per unit length are governed by fabrication considerations. The annulus gap size is determined by pressure drop requirements.

The second plate fin concept, the Corrugated Plate Fin consists of 0.0254 cm (0.01 inch) thick corrugations forming the fins. In this concept there are 10 fins to the inch (~5 fins/cm) and the gap size between inner and outer annulus walls is 0.66 cm (0.26 inches). The corrugations are either welded or brazed to the HSHX walls. Once again the corrugation sizing is governed by fabrication constraints and the gap size by flow considerations.

The heat exchanger(s) terminate in inlet and outlet toroidal headers with a circular cross section of 1.905 cm (0.75 inch) radius. The headers are welded to the HSHX annulus walls. The headers transition to inlet and outlet header ports which manifold the flow to and from the Heat Source Assembly.

Auxiliary cooling inlet and outlet ports are concentric with the HSHX ports to minimize the penetration area through the insulation blanket. The auxiliary coolant flows over the Heat Source in a 0.635 cm (0.25 inch) annulus formed by the Heat Source and the inner wall of the HSHX.

The complete HSA is shown in detail on the drawing of Figure 11-2. The Heat Source and the HSHX are supported off a 0.254 cm (0.1 inch) cylindrical support container which is adjacent to and inboard of the insulation blanket. HSA support fittings are attached to the container to interface with shuttle support hardware. The HSHX is supported off the container by HSHX support frames at both ends. Four HSHX tubular support struts provide torsional stiffness and take out longitudinal launch loads on the HSHX. The frame attachments are designed so that at one end the fitting is fixed to react both longitudinal and transverse loads while the opposite frame takes out only transverse loads. This allows longitudinal growth with minimal induced thermal stresses as the components heat up to operational temperatures.

The Heat Source is supported off the support container by forward and aft Heat Source Supports and End Enclosures ("Spider's"). These are shown in detail in Figure 11-3. The Heat Source Support and End Enclosures are similar in design to the MHW-RTG Heat Source Support and End Enclosures. The Heat Source vent tube passes through the Heat Source Support and angles laterally over the HSHX header. The End Enclosures consist of six spider like radial "I" beams with interconnecting webs. The six mounting feet engage the mounting brackets attached to the support container. Engagement is accomplished by rotating the End Enclosure. The forward End Enclosure is preloaded by rotating a bushing that threads onto the Heat Source Support.

Three quarter turn retaining screws are provided as a redundant component to release the pre-load in event of freeze up of the bushing when removing the Heat Source in orbit.

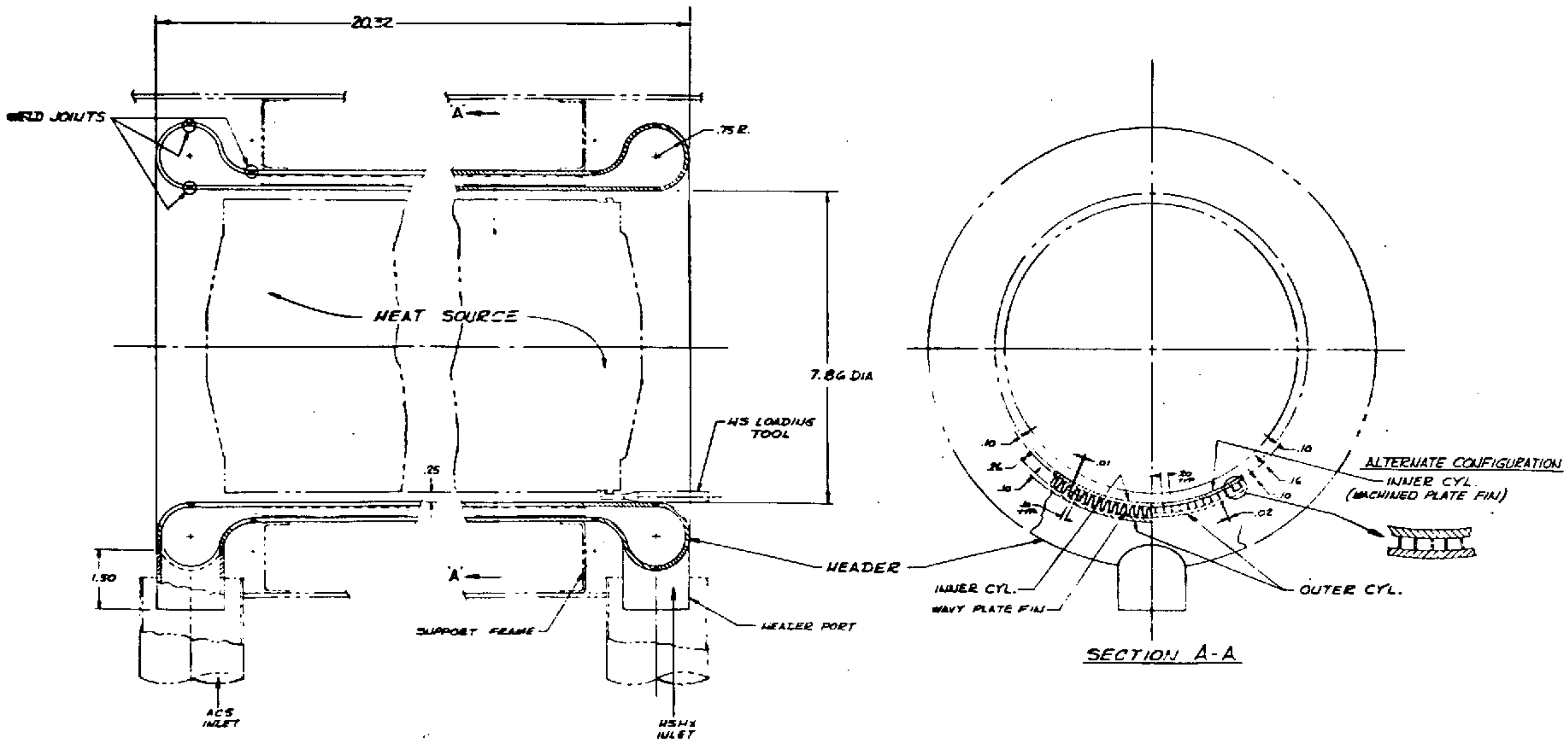


Figure 11-1. Machined and Corrugated Plate Fin Heat Exchangers

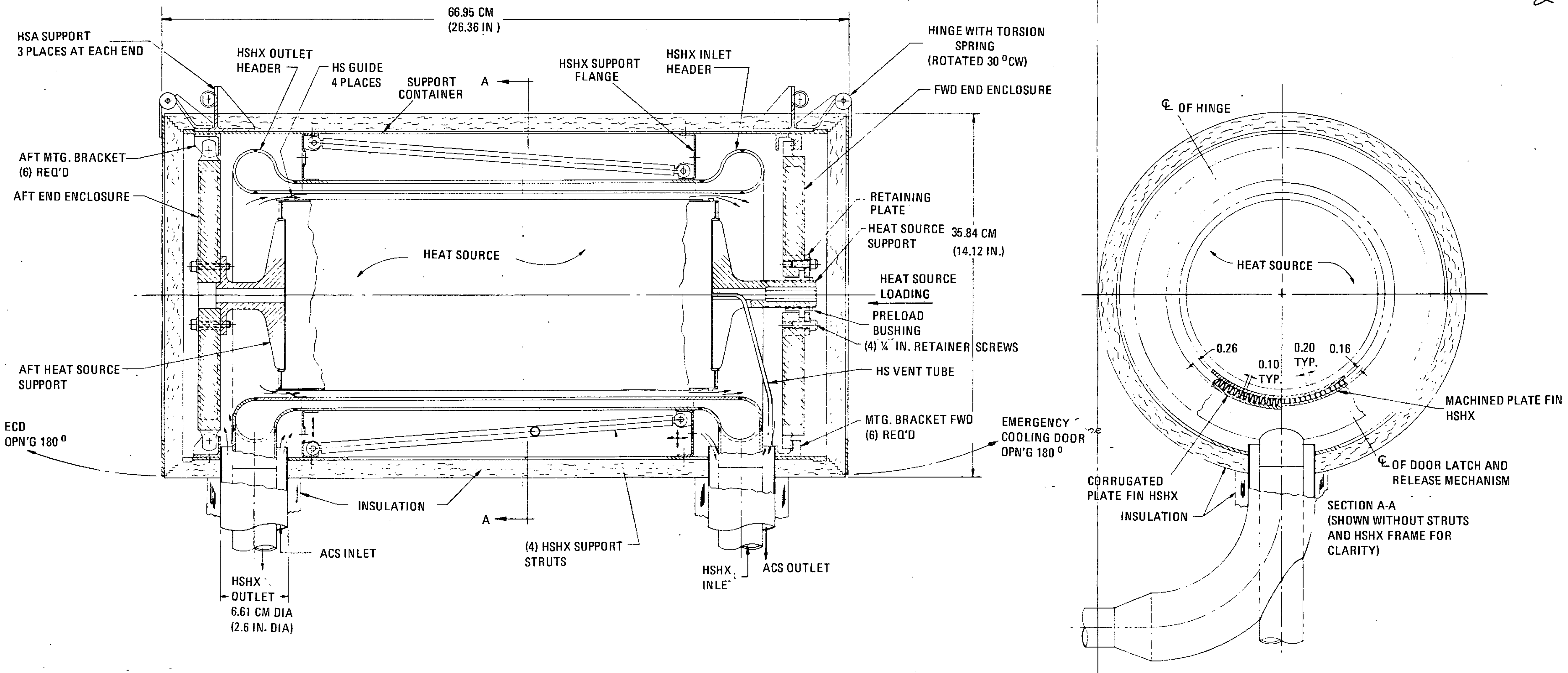


Figure 11-2. Heat Source Assembly

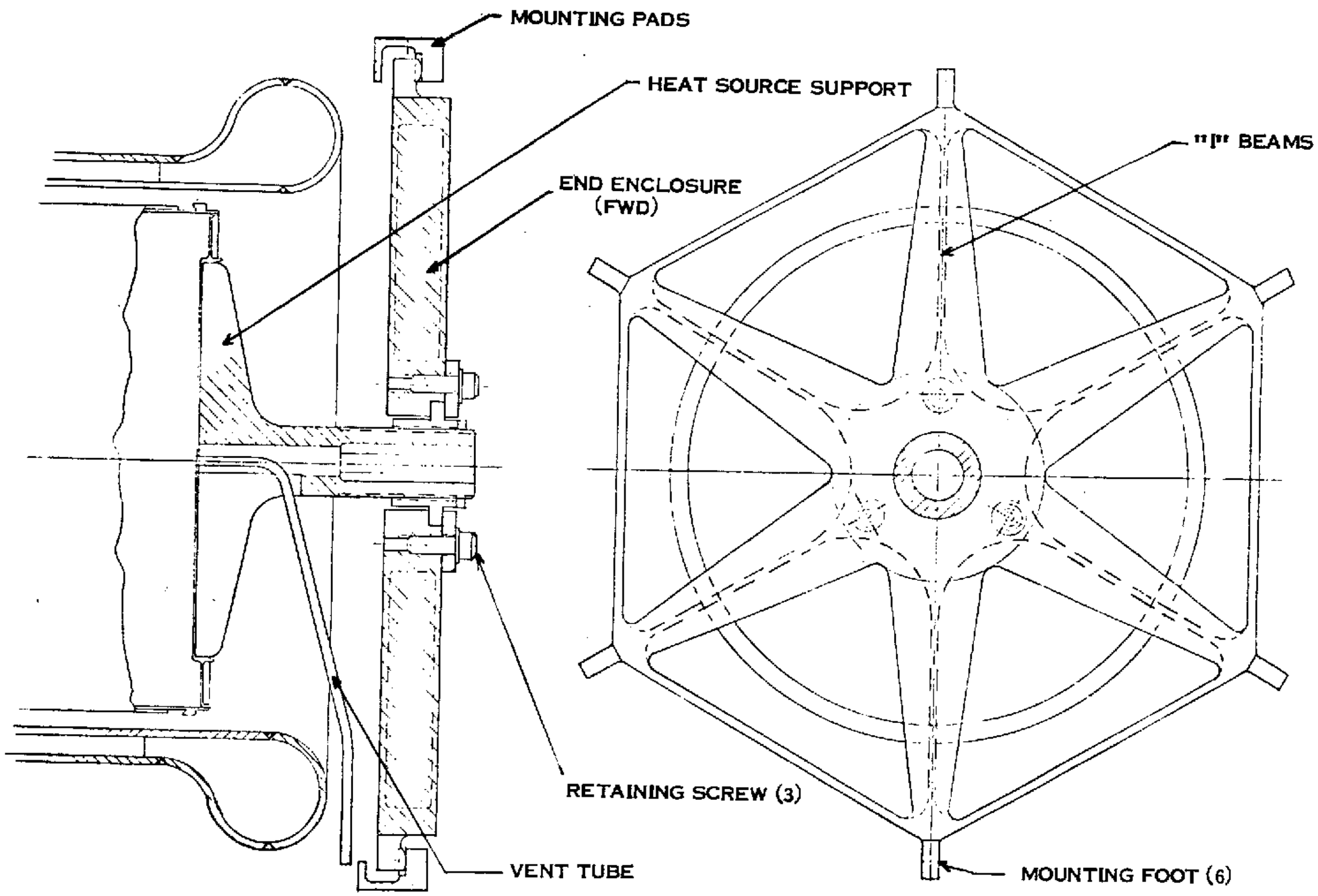


Figure 11-3. Heat Source Support

The aft End Enclosure is identical to the Forward End Enclosure except for the absence of the bushing.

Hinged insulation doors on both ends of the HSA provide emergency cooling when in the open position. The forward end door also serves as the Heat Source loading door. The entire assembly is 66.95 cm (26.36 inches) long with a diameter of 35.84 cm (14.12 inches).

11.1.2 PERFORMANCE AND WEIGHT

11.1.2.1 Pressure Drop

The HSHX flow channels for both the machined plate fin and corrugated plate fin HSHX's are sized so that the pressure drop in the HSHX core for a single HSA Mini-Brayton system is 0.069 N/cm^2 (0.1 psi). The low power Mini-Brayton system (1 HSA) is the one that results in the largest pressure drop through the HSHX core and thus becomes the limiting case for pressure drop design. As discussed in Section 8, a core pressure drop of 0.069 N/cm^2 (0.1 psi) was chosen so that a large fraction of the total pressure drop in the HSA occurs in the Heat Exchanger to assure good flow distributions. The pressure drop contribution due to flow transition from and into the inlet and headers, flow within the headers, and transition from and to the six inch long inlet and outlet ports, is estimated to be 0.082 N/cm^2 (0.12 psi). The total pressure drop for the system is approximately 0.151 N/cm^2 (0.22 psi) which meets the system requirements.

For the high power Mini-Brayton system utilizing 3 HSA's in parallel, including 60 cm (2 feet) of 7.6 cm (3 inch) ID manifolding piping between the HSA's, the pressure drop is estimated to be less than 0.069 N/cm (0.1 psi). This is well below the maximum permissible ΔP of 0.157 N/cm^2 (0.228 psi) for the three HSA systems.

11.1.2.2 Thermal Performance

The temperature distribution along with HSHX wall and Heat Source is given in Figure 11-4 for the machined plate fin design. Temperatures for emissivities of $\epsilon = 0.4$ and 0.8 on the HSHX wall facing the Heat Source, are given. An emissivity of $\epsilon = 0.4$ corresponds to grit blasting the HSHX surface; to obtain an emissivity of $\epsilon = 0.8$ which

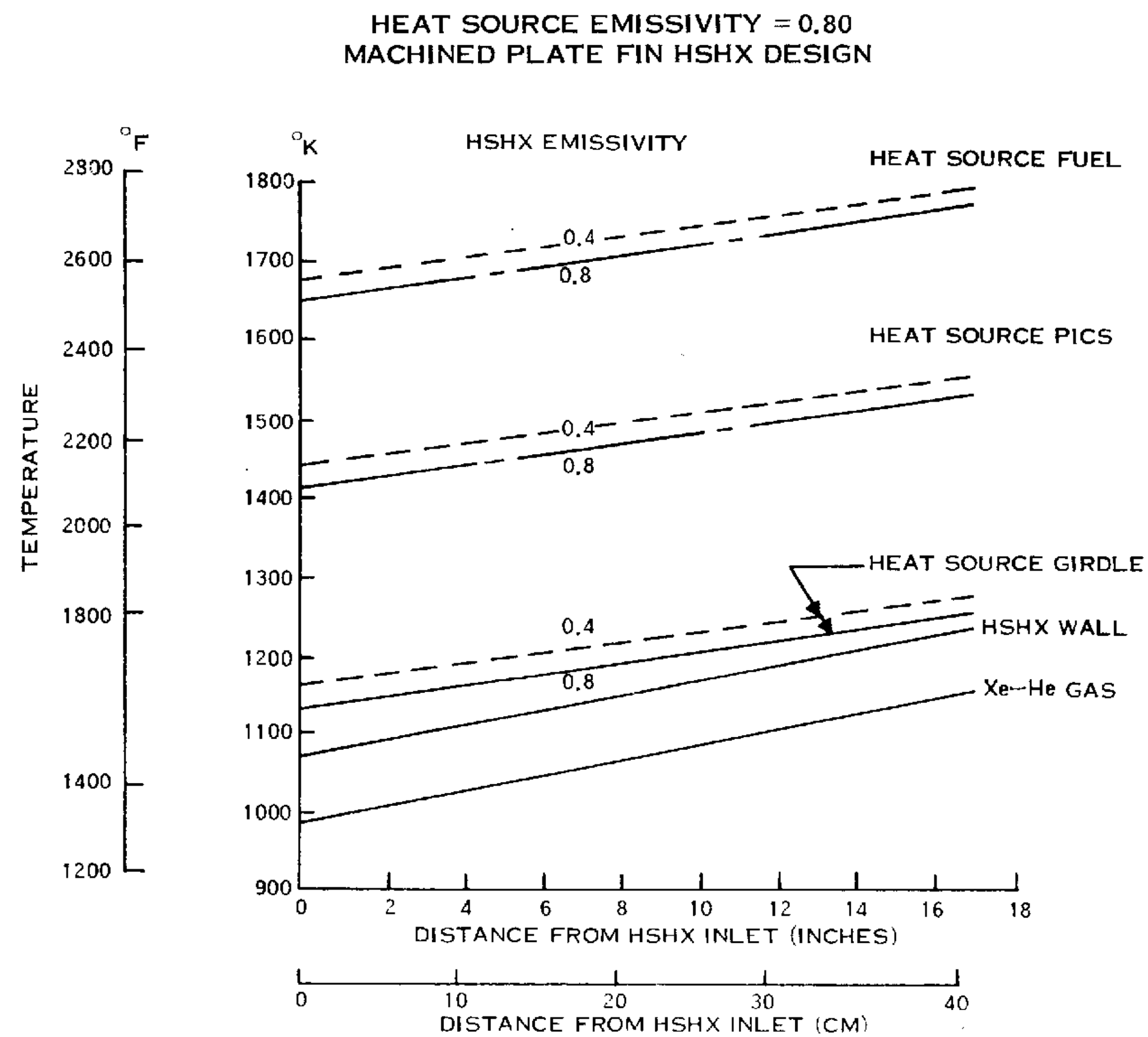


Figure 11-4. Axial Temperature Distribution

would reduce Heat Source temperatures by approximately 30° K (54° F), would require a coating. The maximum Heat Source surface temperature for the machined plate fin designed with $\epsilon = 0.4$ is ~1269° K (1825° F). This is over 100°K (180°F) lower than the specified operating temperature of the Heat Source in the MHW RTG. The temperature distribution for the corrugated plate fin design is similar to the one shown except that all HSHX and heat source temperatures are approximately 39° K (70° F) lower than those shown for the machined plate fin. The lower heat source temperatures result primarily because of the greater heat transfer area provided by the additional number of fins in this design.

11.1.2.3 Weight

An estimate of the weight breakdown for the designs (which are not optimized for minimum weight) are as follows:

	Machine Plate Fin		Corrugated Plate Fin	
	Kg	lb	Kg	lb
Heat Source	21.8	48	21.8	48
Support Container (Cb-103)	16.8	37	16.8	37
Heat Source Support Structure (Cb-103)	5.5	12	5.5	12
HSHX Support Structure (Cb-103)	1.8	4	1.8	4
Insulation Blanket (Moly Foil)	9.1	20	9.1	20
HSHX Headers (Cb-103)	18.6	41	19.5	43
Misc (Cb-103)	4.1	9	4.1	9
HSA Total -	77.7	171	78.6	173

The use of Cb-1Zr does not alter the weight estimate.

11.2 TUBULAR HSA CONCEPT

11.2.1 CONFIGURATION

The axial tube bank Heat Source Heat Exchanger is shown in Figure 11-5. It consists of thirty-five equally spaced 0.95 cm (3/8 in) OD diameter tubes brazed to an inner

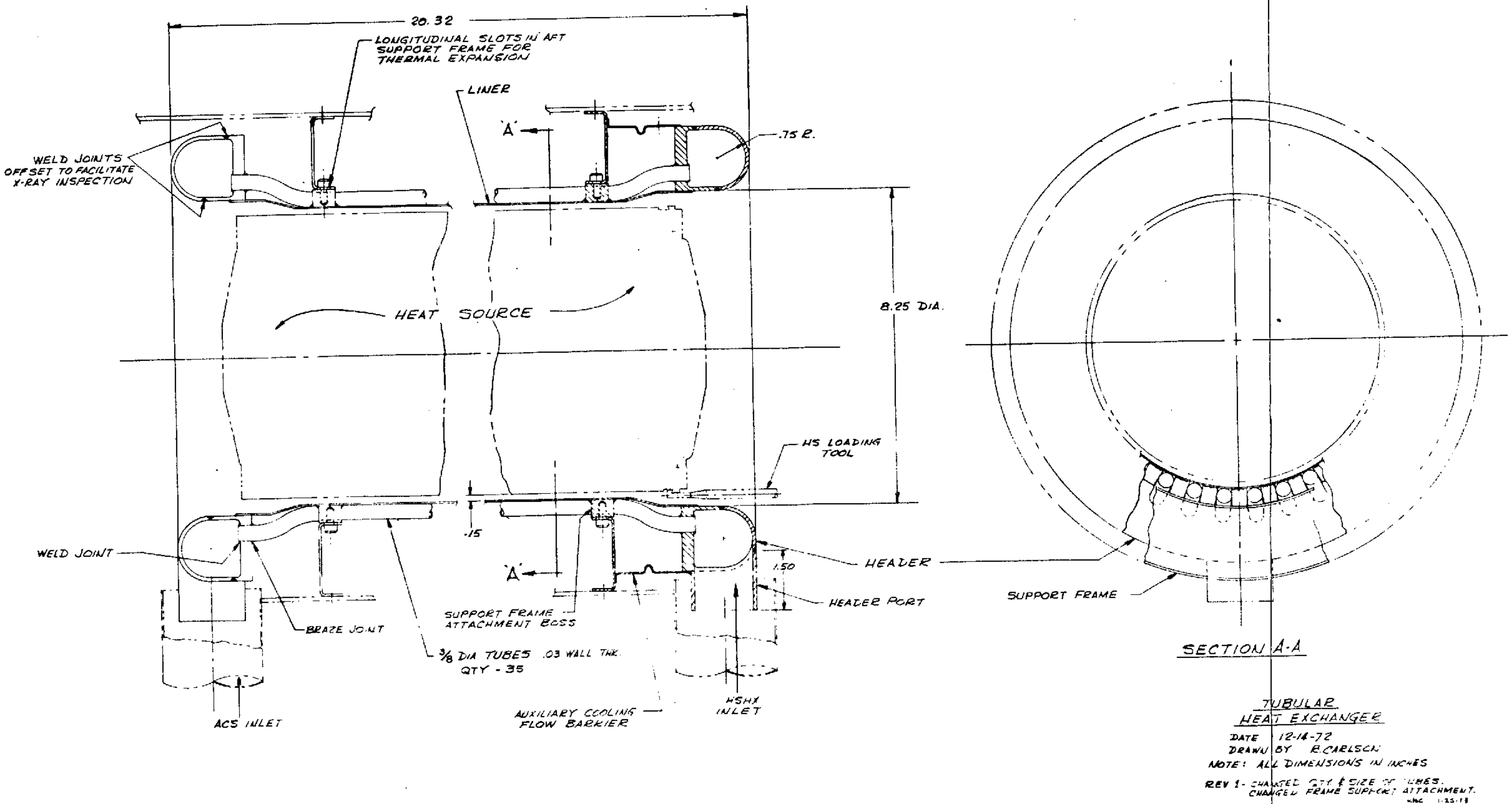


Figure 11-5. Axial Tube Bank Heat Exchanger

liner which along with the Heat Source Surface forms the 0.38 cm (0.15 inch) annular gap for auxiliary cooling flow. The tube walls are 0.076 cm (0.03 inch) thick and are sized for a pressure level of 79 N/cm^2 (115 psi) and the same creep criteria used for the plate fin designs. The tubes terminate in a "D" shaped toroidal header which is formed by 0.76 cm (0.3 inch) thick plate welded to a 1.905 cm (0.75 inch) radius toroidal section. The bend in the tubes near the headers is made to accommodate a MHW type Heat Source loading tool. The HSA Assembly is shown on the drawing of Figure 11-6. The HSHX and HSA support structure and other details of the assembly are essentially identical to the plate fin HSA which is described in paragraph 11.1. The overall length of the HSA is 66.95 cm (26.36 in) and the diameter is 35.84 cm (14.12 in).

11.2.2 PERFORMANCE AND WEIGHT

11.2.2.1 Pressure Drop

The tubular flow area was sized to result in a pressure drop of 0.069 N/cm^2 (0.1 psi) within the HSHX core for the single HSA Mini-Brayton system. The pressure drop contribution of the rest of the HSA system is essentially the same as that given in 11.1.2.1 for the plate fin designs, thus resulting in a total pressure drop of 0.151 N/cm^2 (0.22 psi).

The total pressure drop for a three HSA Mini-Brayton system is approximately 0.069 N/cm^2 (0.1 psi). As with the plate fin designs, pressure drop design limitations are satisfied.

11.2.2.2 Thermal Performance

The thermal response of the HSA is similar to that for the machined plate fin given in Figure 11-4 except that both the tube wall and the Heat Source run approximately 50°K (90°F) higher. The maximum heat source surface temperature for this design with the HSHX $\epsilon = 0.4$ is 1319°K (1915°F), approximately 56°K (100°F) below the MHW specified temperature. The tubular heat exchanger clearly is not as efficient a heat exchanger as the plate fin.

11.2.2.3 Weight

The weight breakdown for the axial tube design (which is not optimized for minimum weight) is as follows:

	Kg	Lb
Heat Source	21.8	48
Support Container (Cb-103)	16.8	37
Heat Source Support Structure (Cb-103)	5.5	12
HSHX Support Structure (Cb-103)	1.8	4
Insulation Blanket (Moly Foil)	9.1	20
HSHX and Header (Cb-103)	12.7	28
Misc. (Cb-103)	4.1	9
	71.8	158

11.3 HSA TRADEOFF

Final selection of an HSA design is based on the following criteria:

1. Reliability of the assembly
2. Minimum Heat Source Temperature
3. Flow Control
4. Minimum Weight
5. Minimum Cost

Reliability is related to the fabrication process and the number of joints in the Heat Exchanger/Header Assembly. Brazing is less attractive than welding because of the introduction of additional alloys which potentially can contaminate welds and create material compatability problems. Minimum Heat Source temperature is desirable to provide added safety design margin for the isotope heat source. Flow control is affected primarily by the dimensional control and stability of the flow channels and is significant because it can influence performance of the system. The fixed cost of the plutonium fueled heat source is the dominant factor in overall HSA cost; the perturbations in total HSA cost due to the different HSHX design is small.

FOLDOUT FRAME 1

FOLDOUT FRAME 2

FOLDOUT FRAME 3

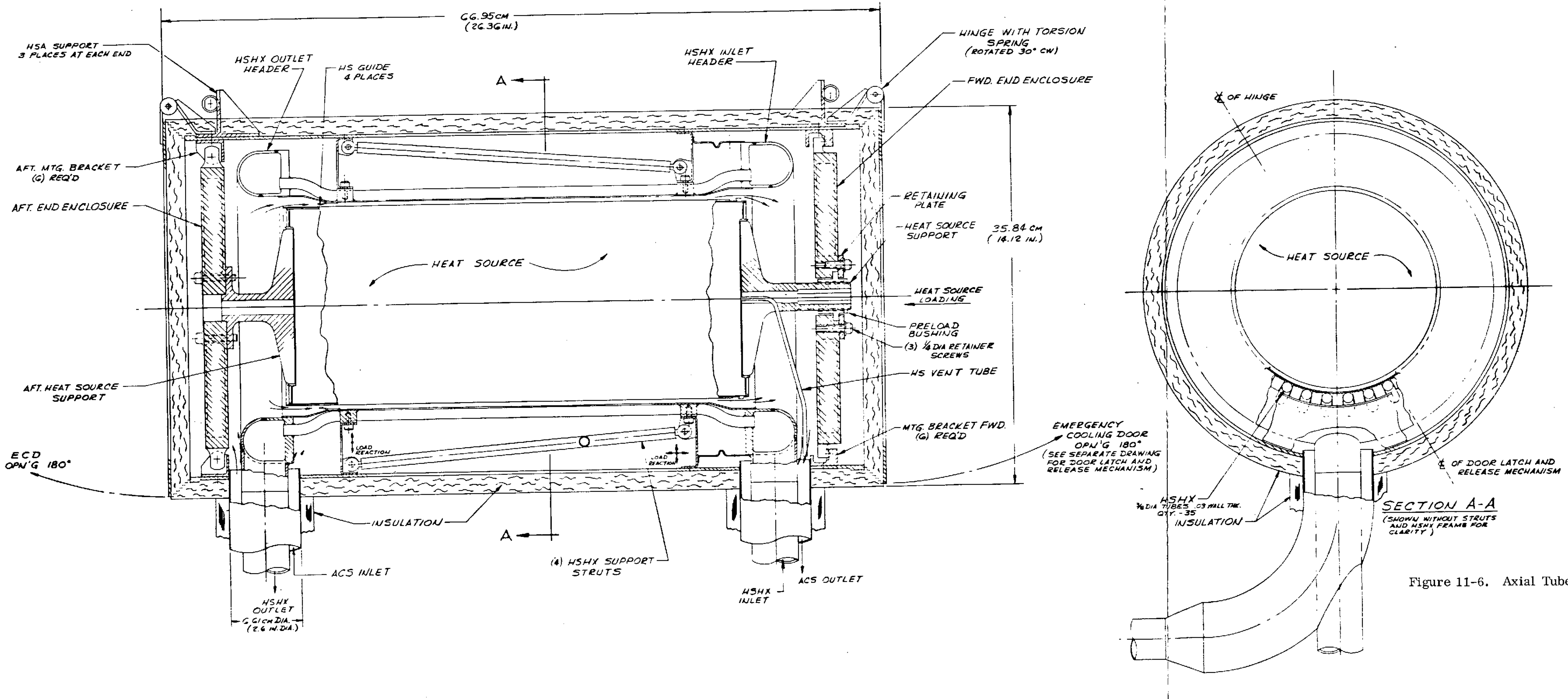


Figure 11-6. Axial Tube Bank HSA

A qualitative comparison of the three HSA designs is summarized in Table 11-1. Relative ratings are indicated by numerals 1 to 3, one being the best rating. Overall, it appears that the machined plate fin is the most attractive design. It offers the simplest and most reliable design from a fabrication point of view; has excellent flow control characteristics; and results in a moderately low Heat Source operational temperature. It may be possible to reduce the Heat Source operational temperature further by incorporating a greater number of machined fins to increase the heat transfer rates to the working fluid.

TABLE 11-1. HSA TRADE OFF COMPARISONS

Criterion \ HSA Design	Machined Plate Fin	Corrugated Plate Fin	Axial Tube Bank	Comments
Reliability	Can be welded design (1)	Brazing required (2)	Brazing rq'd; largest number of joints (3)	
Heat Source Temperature (for HSHX $\epsilon = 0.4$)	1269°K (1825°F) (2)	1230°K (1755°F) (1)	1319°K (1915°F) (3)	
Flow Control	Excellent control and stability of flow channel dimensions (1)	Corrugations offer relatively poor dimensional control and 5-year lifetime stability of flow channels (3)	Excellent control and stability of flow channel dimensions (1)	
Weight	77.7 Kg (171 lb) (2)	78.6 Kg (173 lb) (2)	71.8 Kg (158 lb) (1)	The ~1 Kg difference between the two plate fin designs is within the uncertainty of the preliminary weight calculations
Cost	No significant cost difference for materials and fabrication (1)	(1)	(1)	

SECTION 12

ASSEMBLY AND FABRICATION

This section contains a discussion of manufacturing and assembly consideration for the three candidate HSHX designs. The problem areas, required manufacturing steps, development requirements and costs estimates are presented. Figure 12-1 shows the three final concepts. For the tubular design the fabrication options are all in the techniques of attaching the small axial tubes to the toroidal headers. The options for the plate-fin designs are in the method of attaching the fins to the inner and outer cylinders.

Table 12-1 summarizes the cost estimate for fabrication of each design. These are rough costs intended only for comparison between concepts and not actual estimates of a program to design, build, and qualify the design. The estimated fabrication costs are similar for the designs and fabrication options are such a small part of a reasonable development program that it is concluded that the differences are insignificant.

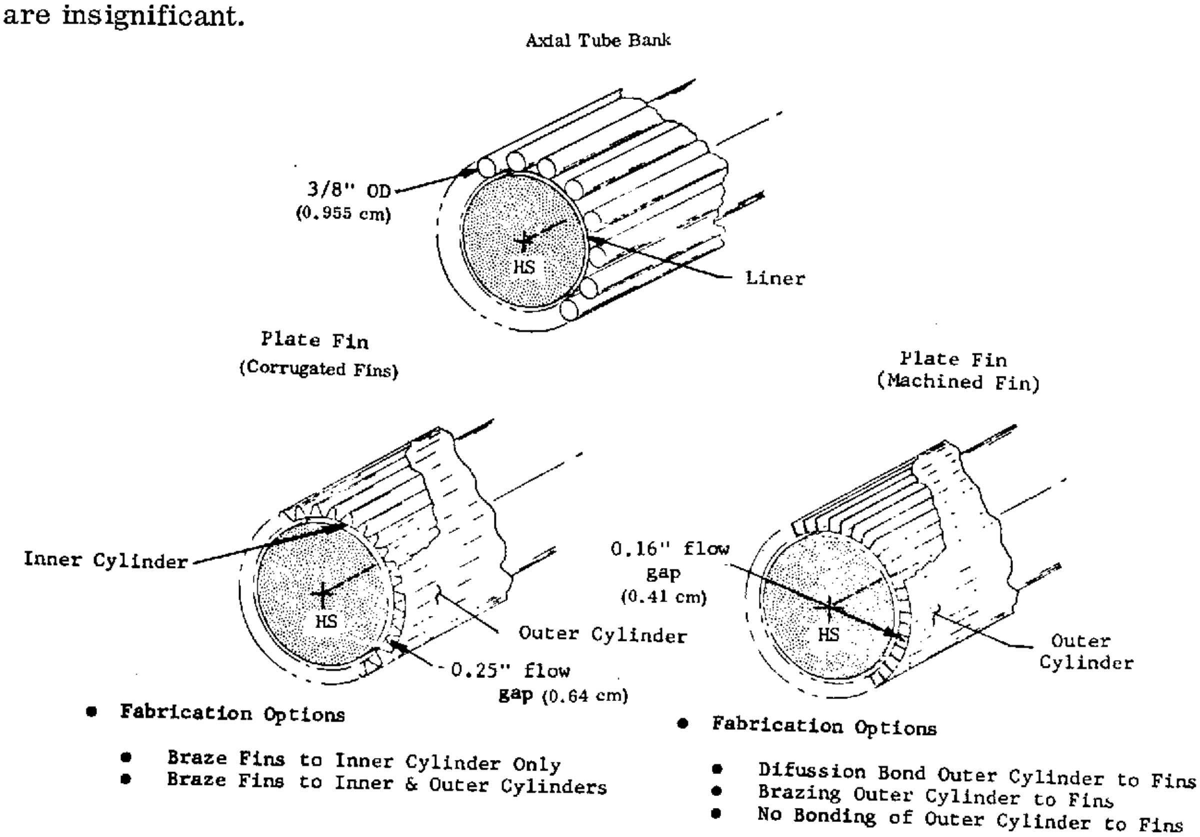


Figure 12-1. HSHX Concepts

TABLE 12-1. HSHX RELATIVE MANUFACTURING COSTS

(Cb-103)

Design	Costs: Labor*	Costs: Fixture & Fab Materials	Costs: Raw Material** Wt Kg	Costs: Raw Material** Wt (lb)	Costs: Raw Material** $	Costs: Total Cost $	Remarks and High Cost Items
Plate Fin Machined Fin Diffusion Bond	11,500	1200	18.6	41	6150	18,850	Machining and added cost for expendable fixturing, pressure bonding, and leaching out molybdenum
No Bond	9,200	1100	18.6	41	6150	16,450	Machining cost
Braze Bond	10,600	1650	18.6	41	6150	18,400	As above plus braze cost
Corrogated Plate Fin Inner Braze	10,600	4850	19.6	43	6450	21,000	High tooling costs, high fixturing costs, and braze costs
Inner/Outer Braze	11,100	4950	19.6	43	6450	22,500	Same as above plus one more braze area
Axial Tube Bank	9,100	4450	12.8	28	4200	17,750	High braze fixture cost (reuseable)

*through overhead

**wt x 3 x $50/lb

12.1 PLATE-FIN HSHX's

Tables 12-2 and 12-3 show the component fabrication and assembly sequence for the diffusion bonded plate-fin design. The machining of the fins is a critical area. The height-to-thickness ratio shown in Figure 11-1 is 8, determined by the fabrication process. If this ratio is much larger, fin breakage becomes a problem. No other area of component fabrication appears unusually difficult.

The assembly sequence involves using molybdenum strips and rings to prevent distortion when the assembly is hot-gas pressure bonded. Moly appears an excellent material for this purpose, since its expansion coefficient is very close to that of the columbium alloys selected (Cb-1Zr, Cb-103), and leachants exist which can remove the moly without attacking the structure. The leaching process is slow but sure, and the result is a monolithic, bonded structure with no braze metal required. The remainder of the assembly procedure is reasonably straightforward.

The variations in fabrication procedure for the machined plate fin design are shown in Table 12-4. Except for the uncertain braze placement, these variations are straightforward. The unbonded outer cylinder option, however, is not as attractive from a long-time performance (flow stability) standpoint.

Table 12-5 shows the fabrication steps required for two versions of the corrugated plate-fin concept. Braze placement and braze quality are potential problems because of the difficulty of applying a full length axial continuous braze and the difficulty of inspecting and repairing the braze if necessary.

The diffusion-bonded machined-fin design concept appears to be an excellent choice from a fabrication standpoint.

12.2 TUBULAR HSHX

The fabrication and assembly of the axial tube bank HSHX, is described in Tables 12-6 and 12-7. The fabrication of the parts is straightforward. However, the attachment of the tubes to the toroidal headers is a critical area. Figure 12-2 shows four joint designs with the pros and cons of each. Joint number two (welded brazed

TABLE 12-2. COMPONENT FABRICATION FOR MACHINED PLATE FIN DESIGN

• Inner Cylinder - Roll form cylinder. Seal weld (GTA or EB). Heat treat/anneal (if required by material). Machine Fins.
• Outer Cylinder - Identical to inner cylinder without fins.
• Header Sections - Die form and machine weld joints with self-fixturing configuration. Drill small hole at inlet tube locations.
• Inlet/Outlet tubes - Stub with maximum length (approximately 1.5") suitable for welding internally from open end. Machined for self-fixturing weld joint.

TABLE 12-3. ASSEMBLY SEQUENCE FOR MACHINED PLATE FIN DESIGN

Diffusion Bond Outer Cylinder to Machined Fins

Fixturing:
Machine moly strips to fit between fins and at ends. Machine expendable covers for sealing areas between inner and outer cylinders. One cover to have small hole for leak checking and evacuation.
Assemble strips between fins on inner cylinder.
Shrink fit inner cylinder to outer cylinder.
Assembly expendable covers; seal weld to inner and outer cylinders.
Helium leak check, evacuate in EB weld chamber, and seal vent hole.
Hot gas pressure bond in autoclave.
Inspect for bond quality.
Remove expendable end covers and leach out moly strips.
Machine weld preps - inner and outer cylinders (consumable in welds).
Weld header sections to inner and outer cylinders.
Weld inlet/outlet tubes to header.

TABLE 12-4. ALTERNATE FABRICATION PROCESS AND ASSEMBLY SEQUENCE FOR MACHINED PLATE FIN DESIGN

- No Bonding of Outer Cylinder to Machined Fins

  Identical to diffusion bonded design except omit steps a, b, d, e, f, g, h (diffusion bond steps) of Table 12-3. Reverse steps c and i. (Machine weld preps before shrink fit of inner and outer cylinders).

- Braze Outer Cylinder to Machined Fins*

  Identical to non-bonded design except:

  After step c of Table 12-3 (fitting cylinders together) -

  1 apply braze alloy

  2 braze in furnace as for Tube-Header design (as in 5th step Table 12-7)

*Full length continuous braze difficult to inspect or repair

TABLE 12-5. FABRICATION PROCESS FOR CORRUGATED PLATE FIN DESIGN

- Braze corrugated Fins to Inner Cylinder Only*
  Similar to non-bonded machined fin design except:

  1 No fins on inner cylinder

  2 Must form corrugated fins

  3 Tack weld fins to inner cylinder to locate accurately

  4 Furnace braze after applying braze alloy

  5 Shrink fit to outer cylinder and continue sequence

- Braze Fins to Inner and Outer Cylinders*

  Similar to above except assemble tack-welded inner tube and fins to outer cylinder before brazing operations.

*Full length continuous braze difficult to inspect or repair

TABLE 12-6. COMPONENT FABRICATION FOR AXIAL TUBE BANK DESIGN

- Tubes - Bend to shape, cut off ends and finish ends.
- Liner - Roll formed (conventional) with one axial seam weld (GTA or EB).
- Header Plates - Machine from plate stock.
- Manifold Tori - Die formed from sheet stock. Weld joints machined for self-fixturing (consumable in weld) with header plate.
- Inlet/Outlet Tubes - Stubs with maximum length (approximately 1.5") suitable for welding internally from open end. Machined for self-fixturing weld joint.

TABLE 12-7. ASSEMBLY SEQUENCE FOR AXIAL TUBE BANK DESIGN

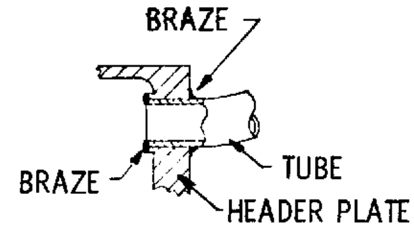
- Align header plates in assembly fixture.
- Insert all tubes in header plates. Strap to liner.
- Weld (GTA or EB) ends of tubes to header plates
- With assembly in brazing fixture, apply brazing alloy.
- Braze in vacuum at 1977° K to 2089 °K (3100 to 3300° F) for five minutes.
- Weld manifold tori to headers.
- Weld inlet/outlet tubes to headers.

joint) was selected for the assembly sequence shown in Table 12-7. In any case, the inner liner must be brazed to the tubes to provide good heat transfer to the HSHX. In Figure 12-2, the degree of joint complexity increases the number one to number four. Only a detailed stress analysis, of the type normally performed in a final design effort, will show which joint design is preferred. It should be emphasized that any one of these designs, or a variation thereof, would certainly provide the necessary strength.

1. All-Brazed Joint

<u>Pro</u>
- Simple, all brazed design

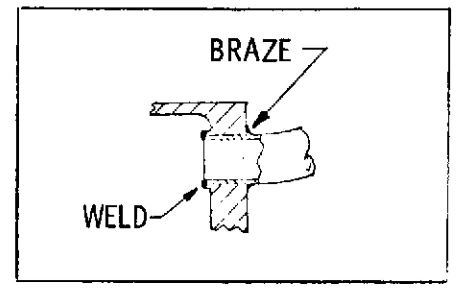
<u>Con</u>
- Braze may contaminate subsequent welds
- High stress concentration possible at Tube-header interface *



2. Weld-Braze Joint

<u>Pro</u>
- No weld contamination

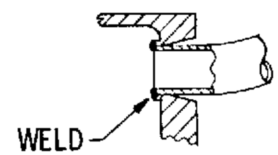
<u>Con</u>
- High stress concentration still possible *



3. All-Welded Joint

<u>Pro</u>
- No braze at joint
- Possible solution to stress concentraction problem

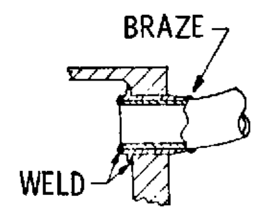
<u>Con</u>
- Not sure will do job *



4. Composite Joint

<u>Pro</u>
- Solves stress problem
- No weld contamination

<u>Con</u>
- Extra pieces and weld steps



* Dependent on results of detailed stress analysis

Figure 12-2. Tube-Header Joint Designs

12.3 FABRICATION EXPERIENCE

Since brazing was considered necessary for the axial tube bank design, the corrugated plate fin design, and some variations of the machined fin design it was necessary to demonstrate that good braze joints could be made without causing grain growth or other detrimental processes in the parent metal. Table 12-8 shows the technical considerations of brazing. Table 12-9 shows various braze alloys which could be considered. Small samples of various refractory alloys were brazed with the AS-540 braze alloy. Figure 12-3 shows the results of various tests on a brazed columbium alloy joint. Figure 12-4 shows the excellent microstructure obtained with Cb-103 and T-111 alloys. Although brazing is less attractive than welding it was concluded that brazing could be successfully performed on any of the candidate designs.

TABLE 12-8. BRAZING AS A MEANS OF STRUCTURE FABRICATION

Major Advantages	Major Disadvantages	Technical Considerations
• Minimal distortion-entire structure uniformly heated	• Introduction of additional alloys	• Metallurgical interactions with parent metal
• Minimal grain growth - no melting parent metal		• Service temperatures
• Minimal aging reactions		• Process & Service environment
		• Wettability and flow
		• Joint Strength
		• Compatability with Coating

TABLE 12-9. BRAZE ALLOYS

Parent Metal/Alloys	Alloy Designation	Alloy Composition	Braze Temp., °K (° F)
Cb Alloy	AS 514	V-35Cb	2144-2172 (3400-3450)
Cb Alloy	-	Ti-400Cb	2144-2172 (3400-3450)
Cb Alloy	AS 546	V-30Cb-10Zr	2033-2061 (3200-3250)
Cb Alloy	AS 547	V29Cb-10Zr-2Si	1977-2005 (3100-3150)
Cb Alloy	AS 501	Ti-30V	1950-1977 (3050-3100)

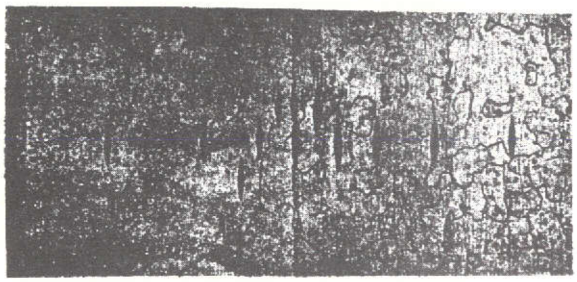
Base Metal: F-48 (Columbium Alloy)

Braze Alloy Designation	Nominal Composition	Melting Range °F Solidus	Liquidus	Ductility As Cast
AS-540	60V-30Cb-10Ti	3200	3300	Ductile

Wettability -

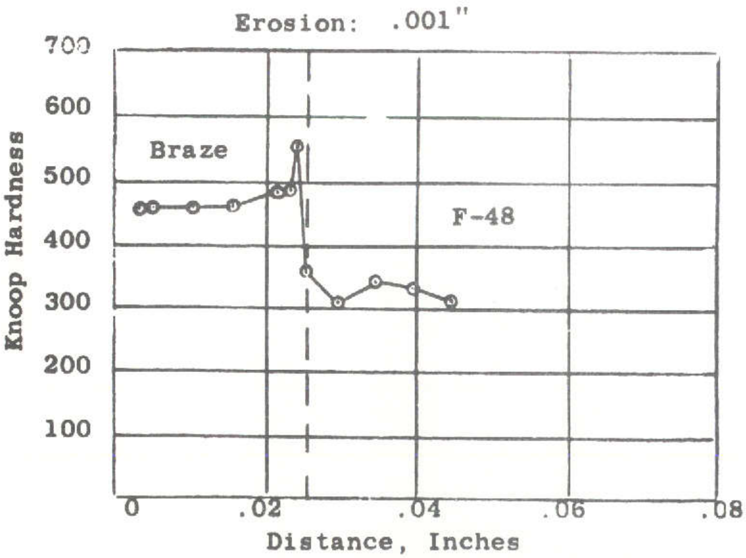
Time 5 Min.
Temperature 3300F
Contact Angle 31°
Mag: 1.25X

Microstructure -

As Brazed 3300F/5 Min.	Heat Treated 2500F/10 hrs.
	
Y2662	Y2952

Hardness Traverse -

As Brazed (3300F/5 Min) | Heat Treated (2500F/10 Hrs.)



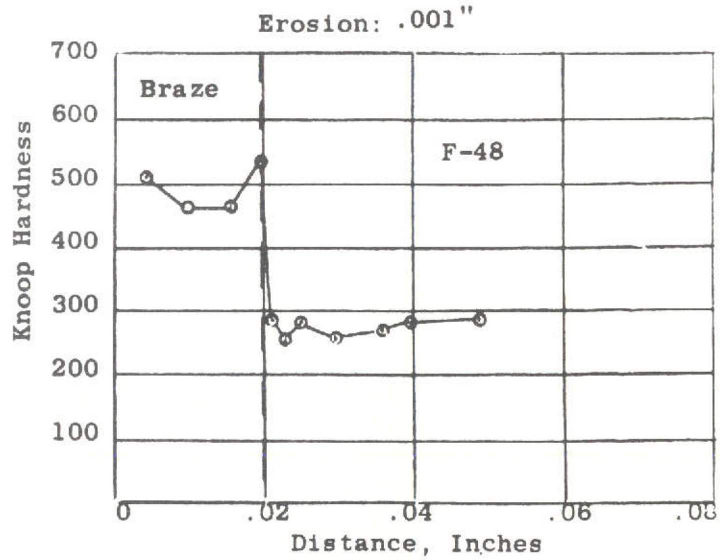
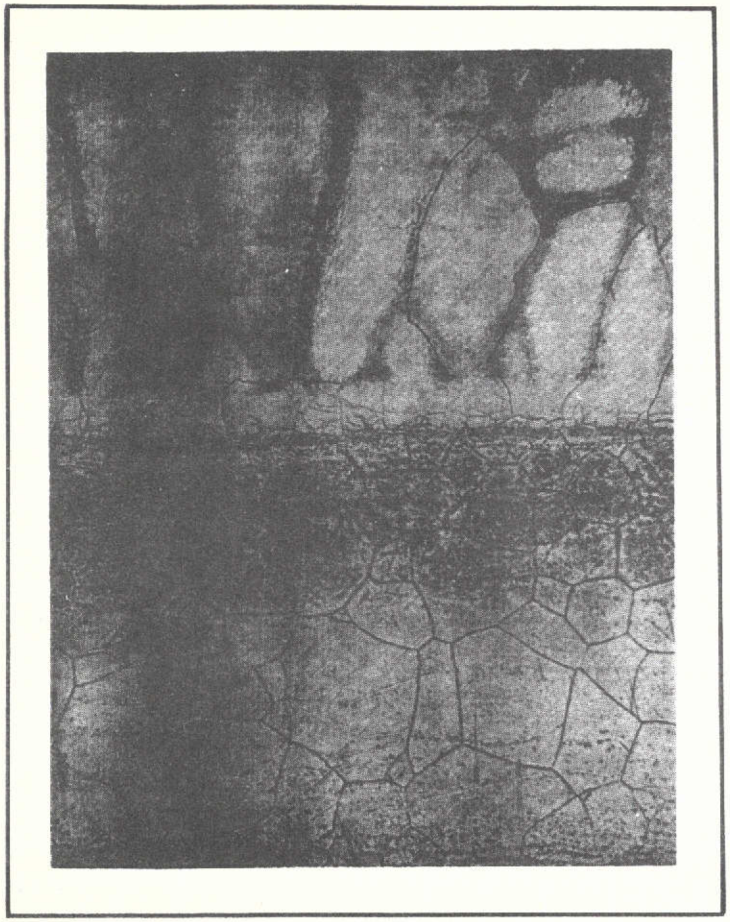
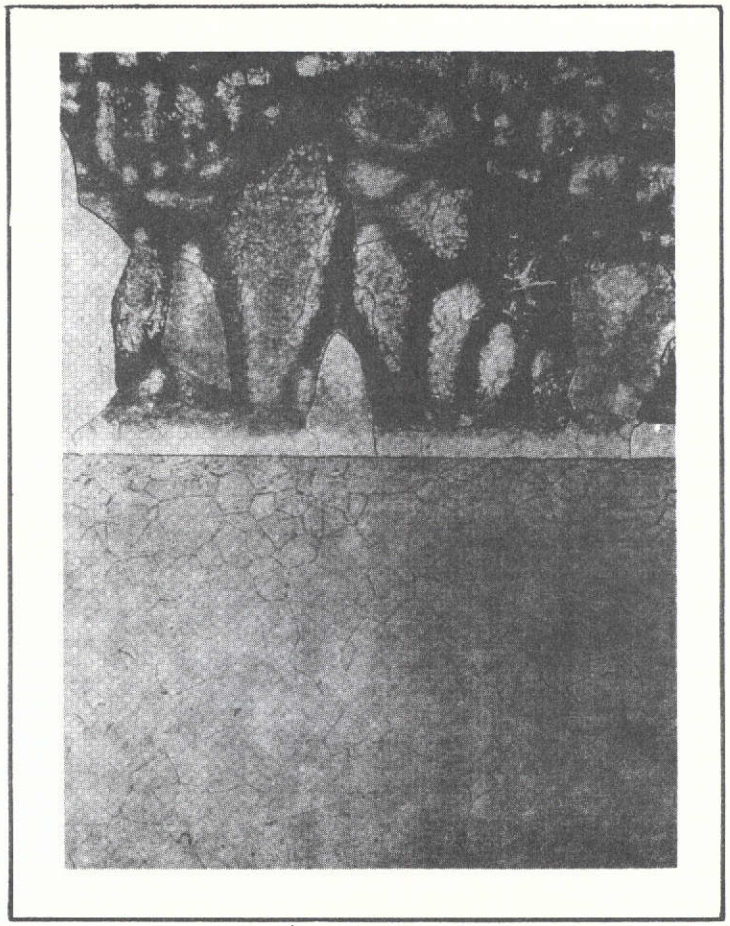


Figure 12-3. Braze Alloy Summary Data Sheet



C-103
Cb-10Hf-10Ti-0.7Zr

AS-540
← 60Cb-30V-10Ti →
3300°F/5 Min



T-111
Ta-8W-2Hf

FIGURE 12-4. GE AS-540 BRAZE ALLOY ON Cb-103 AND T-111 ALLOYS

SECTION 13

SUPPORT EQUIPMENT

Support Equipment for the HSA encompasses both that GSE necessary to handle the Heat Source and HSA on the ground and that equipment required to remove the Heat Source from the assembly in space. Support Equipment was investigated primarily to determine any possible impact on HSA design and to identify existing MHW GSE which can be used for the Mini-Brayton Program.

13.1 GROUND SUPPORT EQUIPMENT

13.1.1 HEAT SOURCE SHIPPING

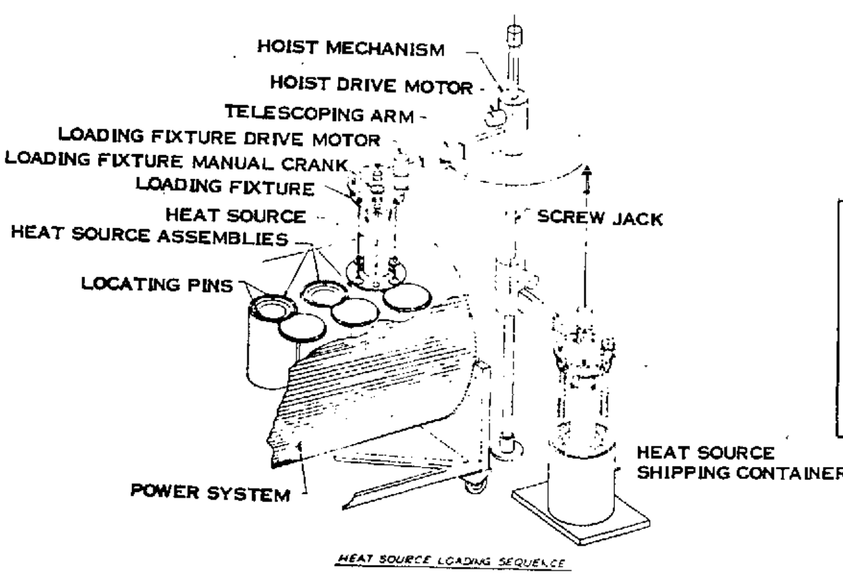
The MHW Heat Source Shipping container can be used, apparently with no modifications, for the Mini Brayton Heat Source. There may be some advantage to subcooling the Heat Source prior to launch to provide added margin in the transient heat up time during ascents. If this is done, it can be accomplished using the shipping container prior to removal with some modification to the gas management system.

13.1.2 HEAT SOURCE LOADING

It is desirable from a safety point of view to load the heat source into the system as late as possible in the countdown. Presumably then, all components of the Mini-Brayton system except the Heat Source will be assembled prior to the Heat Source loading sequence. Figure 13-1 shows a conceptual sketch of a device to load the Heat Source into the HSA. A screw jack hoist mechanism is used in conjunction with the loading fixture (Figure 13-2) to lift the heat source out of its shipping container, swing it over the HSA in the Mini-Brayton Power System and lower it into the HSA. The loading fixture, which interfaces with the Heat Source, is the same as the MHW fixture design with minor modifications. The fixture is designed to engage the three lifting lugs on the heat source and can be designed to load the Heat Source in the horizontal direction as well. The sequence of steps to the load the heat source is as follows.

1. Assemble the aft Heat Source support and End Enclosure Assembly (see Figure 13-2) into the Heat Source Assembly.

2. Assemble the Adapter Ring onto the forward end of the HSA.
3. Open the HS shipping container and load the forward heat source support end enclosure assembly onto the heat source.
4. Position and attach the loading fixture to the HS shipping container.
5. Engage the loading fixture lifting lugs to the HS and take out the end play against the loading fixture spanner wrench.
6. Raise the lifting fixture lug plate to remove the Heat Source from shipping container.
7. Lift loading fixture with HS and position onto adapter ring
8. Lower HS into HSA
9. Rotate forward end enclosure into end enclosure bracket slots using hand tool. (Note: Loading tool prevents heat source support from rotating when rotating forward end enclosure)
10. Preload forward end enclosure bushing with loading fixture spanner wrench to the desired preload and check torque of three retainer screws.
11. Disengage loading fixture lifting lugs and remove fixture.
12. Remove adapter ring.



FEATURES

- Heat source loading fixture same as MHW fixture with minor modifications
- Loading sequence estimated to be 30 minutes

Figure 13-1. Heat Source Loading

HEAT SOURCE LOADING SEQUENCE

1- ASSEMBLE THE AFT HEAT SOURCE SUPPORT AND END ENCLOSURE ASSEMBLY INTO THE HEAT SOURCE ASSEMBLY.

2- ASSEMBLE THE ADAPTER RING ONTO THE FORWARD END OF THE HSA.

3- OPEN THE HS SHIPPING CONTAINER AND LOAD THE FWD HEAT SOURCE SUPPORT AND END ENCLOSURE ASSEMBLY ONTO THE HEAT SOURCE.

4- POSITION AND ATTACH THE LOADING FIXTURE TO THE HS SHIPPING CONTAINER.

5- ENGAGE THE LOADING FIXTURE LIFTING LUGS TO THE HS AND TAKE OUT THE END PLAY AGAINST THE LOADING FIXTURE SPANNER WRENCH.

6- RAISE LIFTING FIXTURE LUG PLATE TO REMOVE HS FROM SHIPPING CONTAINER.

7- LIFT LOADING FIXTURE WITH HS AND POSITION ONTO ADAPTER RING.

8- LOWER HS INTO HSA.

9- ROTATE FWD END ENCLOSURE INTO END ENCLOSURE BRACKET SLOTS USING HAND TOOL. (NOTE: LOADING TOOL PREVENTS HEAT SOURCE SUPPORT FROM ROTATING WHEN ROTATING FWD END ENCLOSURE)

10- PRELOAD FWD END ENCLOSURE BUSHING WITH LOADING FIXTURE SPANNER WRENCH TO THE DESIRED PRELOAD AND CHECK TORQUE OF THREE RETAINER SCREWS.

11- DISENGAGE LOADING FIXTURE LIFTING LUGS AND REMOVE FIXTURE.

12- REMOVE ADAPTER RING.

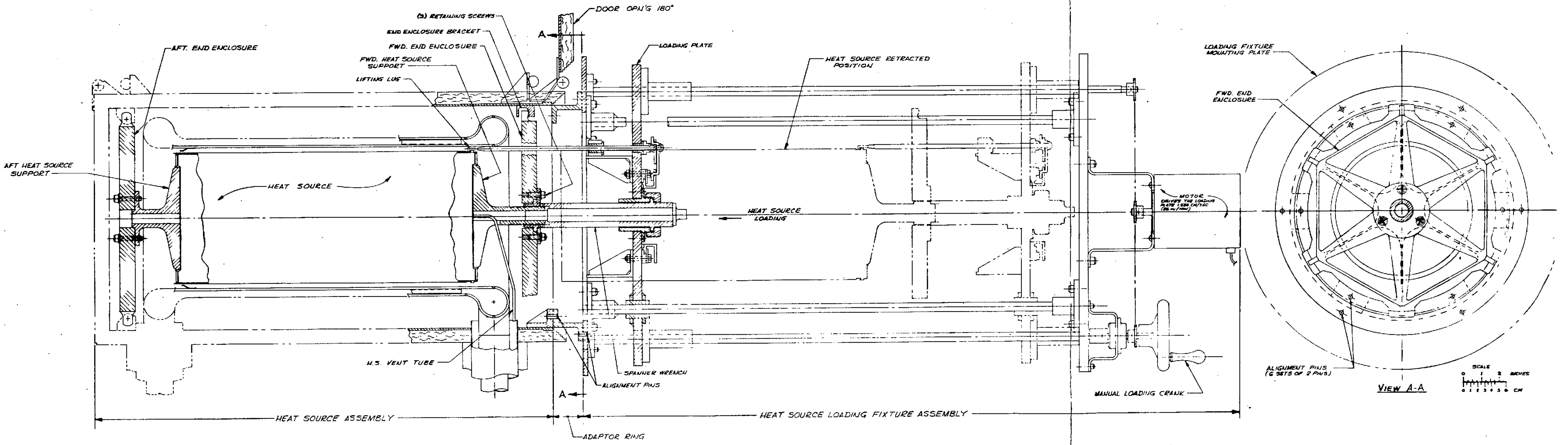


Figure 13-2. Heat Source Loading Fixture

This entire sequence is estimated to take approximately 30 minutes. If the Heat Source is precooled to approximately room temperature prior to loading, Heat Source surface temperatures will remain below 466.5°K (380°F). If precooling is not accomplished, the loading operation must include active cooling of the Heat Source from the time it is taken out of the shipping cask to the time it is inserted in the HSA.

13.2 ORBIT HANDLING

The requirement to be able to remove the Heat Source in orbit leads to the need for an on orbit handling tool. The tool designed for this purpose is very similar to the SNAP 27 astronaut handling tool used in the Apollo mission. Figure 13-3 shows a drawing of the Mini-Brayton tool. It is designed to disengage the Heat Source from the HSA in three different ways in the event of freeze up of HSA mechanical fittings. These options are described in the sequence of operations listed below.

1. Normal Removal Operation
   a. Position tool against forward end enclosure with heat source attachment jaw in outboard position.
   b. Engage heat source assembly structure attachment arm to heat source assembly.
   c. Engage heat source attachment jaw
      (1) Radially to inboard position
      (2) Longitudinally to forward position
   d. Engage and rotate spanner wrench assembly to disengage forward end enclosure, (movement in aft position).
   e. Disengage Heat Source assembly attachment arm.
   f. Remove heat source.
2. Contingency in event of freeze of forward end enclosure bushing at sequence '1d'.
   a. Loosen 3 retainer screws (Quick Release $\frac{1}{4}$ turn screws) with special allen wrench tool
   b. Rotate forward end enclosure to disengage from heat source assembly using special allen wrench.

   Continue sequence 'e' and 'f'.

3. Contingency in event of freeze of 3 retainer screws at sequence 'd1'.

   a. 3d Shear heads of 3 retaining screws with special allen wrench tool.

   b. Continue sequence '2d', 'e' and 'f'.

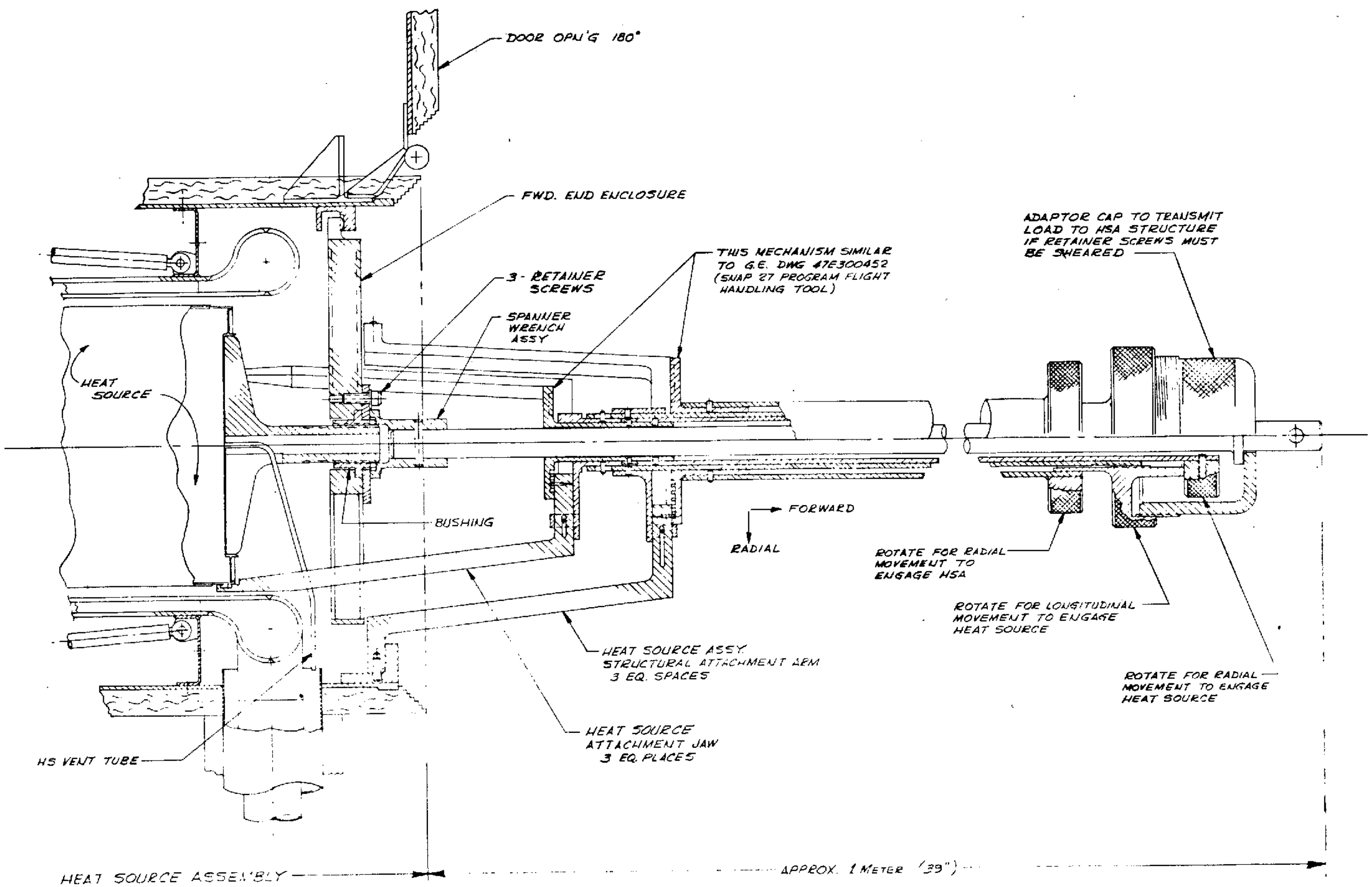
The design of the on-orbit handling tool does not affect the design of the HSA. The requirement to remove the heat source in orbit however does impose design constraints on the HSA and necessitates incorporation of redundant release mechanisms.

FOLDOUT FRAME

1

FOLDOUT FRAME

2



NOTES

1- SEQUENCE OF OPERATION
   A- POSITION TOOL AGAINST FWD. END ENCLOSURE WITH HEAT SOURCE ATTACHMENT JAW IN OUTBOARD POSITION.
   B- ENGAGE HEAT SOURCE ASSEMBLY STRUCTURE ATTACHMENT ARM TO HEAT SOURCE ASSEMBLY.
   C- ENGAGE HEAT SOURCE ATTACHMENT JAW
      • RADIALLY TO INBOARD POSITION
      • LONGITUDINALLY TO FORWARD POSITION
   D- ENGAGE AND ROTATE SPANNER WRENCH ASSEMBLY TO DISENGAGE FWD. END ENCLOSURE, (MOVEMENT IN AFT POSITION).
   E- DISENGAGE HEAT SOURCE ASSEMBLY ATTACHMENT ARM.
   F- REMOVE HEAT SOURCE.

2- CONTINGENCY IN EVENT OF FREEZE OF FWD END ENCLOSURE BUSHING AT SEQUENCE "D".
   D1- LOOSEN 3 RETAINER SCREWS WITH SPECIAL ALLEN WRENCH TOOL.
   D2- ROTATE FWD END ENCLOSURE TO DISENGAGE FROM HEAT SOURCE ASSEMBLY USING SPECIAL ALLEN WRENCH.
   CONTINUE SEQUENCE "E" AND "F".

3- CONTINGENCY IN EVENT OF FREEZE OF 3 RETAINER SCREWS AT SEQUENCE "D1".
   D3- SHEAR HEADS OF 3 RETAINING SCREWS WITH SPECIAL ALLEN WRENCH TOOL.
   CONTINUE SEQUENCE "D2", "E" AND "F".

Figure 13-3. On Orbit Handling Tool

SECTION 14
CONCLUSIONS

Three candidate HSA design concepts which satisfy all imposed design and safety requirements have been developed utilizing the MHW 2400 W(t) Heat Source. The designs differ in Heat Source Heat Exchanger configuration; one concept incorporates a bank of 35 tubes, the other two are plate fin heat exchangers. The recommended HSHX is a machined plate fin, diffusion bonded design which can be fabricated without brazing. The complete HSA weighs 78 Kg (171 lb) and operates with a maximum steady state Heat Source temperature of (1269°K) 1825°F, which is 104°K (187°F) less than the MHW specified operating temperature. It is anticipated that detailed design optimization will result in lower weights. Auxiliary Cooling is effected on the launch pad by passing a coolant gas such as dry Nitrogen, directly over the Heat Source in the annulus formed by the Heat Source Emmissivity Sleeve and the HSHX. The Heat Source can be easily maintained below 500°K (440°F) and exposed surfaces below 466.5°K (380°F) during this prelaunch phase of the mission. Emergency cooling in the event of a Heat Source over-temperature condition is accomplished by the automatic opening of two insulated end doors on either side of the HSA. The materials recommended for the HSHX, as well as for those structural support components of the HSA which are within the insulation enclosure, is either of the Columbium refractory alloys, Cb-103 or Cb-1Zr. Both materials are essentially equivalent in overall performance. However long term (5 year) creep stress property data at operational temperatures is lacking and a test program will be required to completely characterize either of the candidate materials.

The HSA can be used singly or in parallel with one or two additional HSA's to provide output powers of 500 W(e), 1200 W(e) and 2000 W(e) (nominal). Two year grounds test of the Mini-Brayton System would require that the HSA be either situated in a vacuum chamber or in an inert gas environment to preclude oxidation of the recommended refractory alloys.

It is concluded that the HSA design concepts generated during this study program are feasible designs; can be fabricated into reliable assemblies; and can be integrated into a Mini-Brayton Power System which will provide a long life versatile power system for future spacecraft.

SECTION 15

REFERENCES

1. "Space Shuttle Baseline Accommodations for Payloads". - MSC - 06900, July 27, 1972

2. Multi Hundred Watt Radioisotope Thermoelectric Generator Program - Preliminary Safety Analysis Report - Volume II Accident Model Document, Document No. GESP 7076; GEMS-407, July 1972

3. Berry, C.A. and Rose, R.G.; "Radiation Dose Limits for Manned Space Flight in Skylab, Shuttle and Space Station/Base Programs" - letter to distribution, Jan. 1971

4. Humphreys Jr, J.W.; "Radiation Exposure Criteria/or Space Vehicle Design Studies" - letter to distribution March 1971

5. Loffreda, L.A.; "MHW Heat Source Dose Rates" - GE PIR 3930, 4/5/72

6. Space Shuttle System Summary Briefing, July 8, 1972; North American Rockwell Space Division Report

7. Lynahan, P.W.; "Explosion Fragmentation Shielding for Mini-Brayton Nuclear Heat Source" - GE PIR 4337, 1/22/73

8. Intentionally omitted

9. "Evaporation of Iron, Nickel and Cobalt Base Alloys at 760°C to 980°C in High Vacuum", ORNL Report 3677

10. "Manned Space Flight Nuclear System Safety" - Final Report, Jan 1972, Contract NAS 8-26283, General Electric Company 72SD4201

APPENDIX A

ACRONYMNS

ACS	Auxiliary Cooling Subsystem
BRU	Brayton Rotating Unit (Turbine - Alternator - Compressor Assembly)
EB	Electron Beam (Welding)
ECD	Emergency Cooling Device (A device which automatically releases the emergency cooling doors)
ECS	Emergency Cooling Subsystem (The combination of ECD and Emergency Cooling Doors for the Space Shuttle mission or melting insulation for the Titan IIIC mission)
FFBD	Functional Flow Block Diagram
GSE	Ground Support Equipment
GTA	Gas Tungsten Arc (Welding)
HS	Heat Source
HSA	Heat Source Assembly
IGS	Inert Gas Subsystem (Identical to the ACS with the use of a pure inert gas and appropriate valving as required).

APPENDIX B

SAFETY REQUIREMENTS AND GUIDELINES

B. 1 FORMAT

Figure B-1 shows the format used in presenting safety requirements and guidelines.

B. 2 NUMBER

The identifying alphanumerical designation consists of two letters followed by a sequential number.

Requirement (G - Guideline)

Design Feature (0 - Operations Feature)

Numerical Designator

RD-1

The first alpha character denotes whether the statement is a mandatory requirement (R) for a Guideline (G). The second alpha character distinguishes between design considerations (D) or operational procedures (0). The numbers run sequentially for requirements and guidelines.

B. 3 FUNCTION

The function number and function name denote the functions from the FFBD of Figure 3-3 to which the requirement or guideline is pertinent.

B. 4 OPERATION

The operation block is used to denote the particular operation (lower level function) to which the guideline is directed. A typical operation category is isotope cooling.

B. 5 MISSION PHASE/EVENT

The phase or phases of the mission for which the guideline applies is listed. In general, they correspond to top level functions of Figure 3-3.

CLASSIFICATION	CLASSIFICATION NUMBER	PROGRAM ELEMENT	TITLE
REQUIREMENTS (DESIGN)	RD-1	HSA/Mini-Brayton/GSE	On Pad and Landing Site Cooling of Heat Sources.
	RD-2	HSA	Heat Source Cooling System
	RD-3	HSA	Heat Source Emergency Cooling
	RD-4	HSA	Blast and Fragmentation Protection
	RD-5	HSA	Fireball and Solid Fire Protection
	RD-6	HSA Shuttle P/L Integration	Shuttle Crew: Radiation Exposure Control
	RD-7	HSA/Shuttle	Payload Status Monitoring
GUIDELINES (DESIGN)	GD-3	Mini-Brayton Support Equipment	Transfer Module
GUIDELINES (OPERATIONAL)	GO-3	Mission Planning	Quick Retrieval Operations
	GO-4	Mission Planning	In-Orbit Repairs

Figure B-1. Safety Requirement and Guideline Format

B.6 <u>REQUIREMENT ALLOCATION</u>

This block indicates the program element, e.g., Shuttle, GSE, Mini-Brayton HSA, etc., to which the safety requirement is allocated. If a requirement is allocated to the Mini-Brayton HSA, for example, it implies a HSA design requirement.

B.7 <u>TITLE</u>

The title is provided to briefly identify the subject matter of the guideline. It is used to provide the necessary descriptive words to concisely identify the guideline and content.

B.8 <u>REQUIREMENT OR GUIDELINE</u>

The statement contains the requirement or guideline, and is usually a brief statement, which describes a suggested means by which a hazard may be alleviated or eliminated.

B.9 <u>POTENTIAL HAZARD</u>

This block contains a brief definition of the nature of the potential hazard(s) presented.

B.10 <u>REMARKS/INTEGRATION CONSIDERATIONS</u>

This block is intended to provide additional information needed to further define the guideline, indicate integration problems, or to indicate techniques worthy of consideration which could be applied to eliminate the hazard.

B.11 <u>REFERENCES</u>

The key references (supporting data) in the Manned Space Flight Nuclear System Safety study final report Contract NAS8-26283 (Ref. 10) or other related documents which are used to arrive at the guidelines are listed.

B.12 <u>CROSS REFERENCES</u>

The cross reference column lists related guidelines in the appendix.

B.13 <u>SAFETY REQUIREMENTS/GUIDELINES</u>

The set of safety requirements and guidelines are given, along with an index, in the following pages.

INDEX OF SAFETY GUIDELINES AND REQUIREMENTS

Classification	Classification Number	Program Element	Title
Requirements (Design)	RD-1	HSA/Mini-Brayton/GSE	On Pad and Landing Site Cooling of Heat Sources.
	RD-2	HSA	Heat Source Cooling System
	RD-3	HSA	Heat Source Emergency Cooling
	RD-4	HSA	Blast and Fragmentation Protection
	RD-5	HSA	Fireball and Solid Fire Protection
	RD-6	HSA Shuttle P/L Integration	Shuttle Crew: Radiation Exposure Control
	RD-7	HSA/Shuttle	Payload Status Monitoring
Guidelines (Design)	GD-3	Mini-Brayton Support Equipment	Transfer Module
Guidelines (Operational)	GO-3	Mission Planning	Quick Retrieval Operations
	GO-4	Mission Planning	In-Orbit Repairs
	GO-5		

SAFETY GUIDELINE

NO.	DATE:
RD-1	Sept. 1972
	REVISION:

FUNCTION NO.	FUNCTION NAME	OPERATION
6.1 1.7 1.8	Survive Pre-Launch Environment Transfer Shuttle Orbiter to MRF Remove, Service or Dispose of P/L	Heat Source Cooling at Launch Pad and Landing Site

MISSION PHASE/EVENT

Pre-Launch; Recovery

REQUIREMENT ALLOCATION

Mini-Brayton GSE and HSA

TITLE: ON PAD AND LANDING SITE COOLING OF HEAT SOURCE

GUIDELINE

Maintain the external surface areas of the Heat Source Assembly below 466.5°K (380°F) during Pre-Launch operations and Landing site operations. The HSA shall be designed to interface with the GSE.

POTENTIAL HAZARD:

On a standard day at sea level, the radiating surface of an uncooled heat source can reach an equilibrium temperature in excess of 867°K (1100° F). This would present a hazardous condition in the presence of booster fuels.

REMARKS/INTEGRATION CONSIDERATIONS:

Cooling during pre-launch and at the landing site can be accomplished by pumping cold nitrogen or other similar inert fluid over the heat source. The cold nitrogen can be supplied by launch pad/ landing site GSE that interfaces with the Heat Source Assembly's Auxiliary Cooling Heat Exchanger.

REFERENCES:

CONTRACT NAS 8-26283 (Manned Space Flight Nuclear System Safety)

DOCUMENTS: 72SD4201-4-1, Section 4, 5, Appendix C.

SAFETY GUIDELINE NO. RD101 (72SD4201-5-2).

CROSS REFERENCES:

RD-2

SAFETY GUIDELINE

NO.	DATE:
RD-2	Sept. 1972
	REVISION:

FUNCTION NO.	FUNCTION NAME
5.1	Survive Launch Environment
4.1	Survive Shuttle Orbiter Environment
2.1	Survive Remote Orbital Environment
1.4	Perform Shuttle Orbiter Re-entry
1.5	Perform Shuttle Orbiter Landing
1.6	Perform Shuttle Orbiter Safing

OPERATION

Heat Source Cooling After Lift-Off

MISSION PHASE/EVENT

Launch/Ascent; On Orbit Operations; Re-entry; Landing

REQUIREMENT ALLOCATION

Heat Source Assembly

TITLE: HEAT SOURCE COOLING SYSTEM

GUIDELINE

The Heat Source Assembly shall include active and/or passive cooling systems capable of maintaining the external surface areas of the heat source below ~1367° K (2000° F) during ascent and subsequent mission phases.

POTENTIAL HAZARD:

An isotope heat source provides a continuous flow of heat energy throughout its lifetime. The heat must be removed in a manner that maintains the temperature of the heat source and nearby equipment at acceptably low levels. Inadequate heat removal will result in excessive temperatures that can render equipment unoperative and the heat source capsule unable to contain the isotope fuel.

REMARKS/INTEGRATION CONSIDERATIONS:

During launch, while the power module (BRU) is shut down, an active cooling system may be required. Heat source cooling could be accomplished if required during this phase by a low temperature Nitrogen system similar to that used during pre-launch but carried on board. During on orbit operations, passive cooling (direct radiation to space) can be employed once the Shuttle P/L doors are opened and provided environmental shielding does not preclude a view of space. During re-entry, when the Shuttle P/L doors are closed, cooling of the heat source can be accomplished by the low temperature Nitrogen system or by a water boil-off system. Upon landing, Heat Source Cooling would be accomplished by GSE once access to the Payload Bay is available.

REFERENCES:

CONTRACT NAS 8-26283

DOCUMENTS: 72SD4201-4-1 Sections 4, 5; Appendix C; 72SD4201-2-1 Sec. 5

SAFETY GUIDELINE NO. RD-102; (72SD4201-5-2)

CROSS REFERENCES:

RD-1

SAFETY GUIDELINE

NO.	DATE:
RD-3	Sept. 1972
	REVISION:

FUNCTION NO.	FUNCTION NAME	OPERATION
5.1 4.1 1.4	Survive Launch Environment Survive Shuttle Orbiter Environment Perform Shuttle Orbiter Re-entry	Heat Source Cooling Contingency

MISSION PHASE/EVENT	REQUIREMENT ALLOCATION
Launch/Ascent; On Orbit Operations, Re-entry, Landing	Heat Source Assembly

TITLE: HEAT SOURCE EMERGENCY COOLING

GUIDELINE

Provide a redundant Heat Source cooling system as part of the Heat Source Assembly, to be operable during all mission phases in event of failure of the primary cooling system within the Shuttle.

POTENTIAL HAZARD:

Excessive temperatures causing breach of the isotope fuel container could result from failure of the prime cooling system.

REMARKS/INTEGRATION CONSIDERATIONS: The following are candidates for the Emergency Cooling Device: (1) A thermostatically activated door on the HSA which exposes uninsulated areas of the HS to the Shuttle payload bay walls; (2) Cold gas and/or water boil off system utilizing a pumped loop which rejects heat to the Shuttle payload bay during ascent and perhaps during re-entry when higher Shuttle wall temperatures exist. Suitable controls can permit the pumped loop to act as a water boil-off system, if necessary, during re-entry; (3) Energy absorption (change in phase) system possibly utilizing the HSA insulation material (contamination effects on other payloads in the orbiter payload bay should be considered); (4) Heat pipes to conduct heat to the Shuttle radiating panels. Effects of elevated radiating panels should be considered.

REFERENCES:	CROSS REFERENCES:
CONTRACT NAS 8-26283 DOCUMENTS: 72SD4201-4-1, Sections 4, 5, 6, Appendix C SAFETY GUIDELINE NO. RD-103 (72SD4201-5-2)	RD-2

SAFETY GUIDELINE

NO.	DATE:
RD-4	Sept. 1972
	REVISION:

FUNCTION NO.	FUNCTION NAME	OPERATION
6.4	Survive Pre-Launch Explosion Environment	Transporting Payload in Shuttle
5.3	Survive Launch Explosion Environment	
1.3	Survive Uncontrolled Orbiter Re-entry and Impact	

MISSION PHASE/EVENT	REQUIREMENT ALLOCATION
Pre-Launch, Launch/Ascent, Re-entry	Heat Source Assembly

TITLE: BLAST AND FRAGMENTATION PROTECTION

GUIDELINE

Provide adequate blast overpressure and fragmentation protection to assure containment of all radioactive material in event of a Shuttle explosion.

POTENTIAL HAZARD:

The proximity of the isotope payload in the Shuttle cargo bay to the Shuttle fuel tankage may result in extremely high blast overpressures and fragment velocities in the event of a tankage explosion. To prevent breaking of the isotope fuel capsules and the release of radioactive material to the environment, shielding may be required (unless the heat source can be shown to survive the severe environment without shielding).

REMARKS/INTEGRATION CONSIDERATIONS:

Three possible approaches to the design of a blast shield (protection of heat source capsules from the blast overpressure, high velocity fragments, and fireball temperatures that might ensue in the event of an explosion of the Shuttle main tankage) are:

- Hemispherical shield - interface shielding between the heat source and Shuttle tankage; permits passive thermal control.
- 4π shield - heat source is completely protected by shielding.

(Continued next page)

REFERENCES:
CONTRACT NAS 8-26283
DOCUMENTS: 72SD4201-4-1 Section 4, 5, Appendix A; 72SD4201-4-2, App. A.
SAFETY GUIDELINE NO. RD-104 (72SD4201-5-2).

CROSS REFERENCES:
RD-5

SAFETY GUIDELINE	NO. RD-4 (Cont.)	DATE: Sept. 1972 REVISION: A May 15, 1973

FUNCTION NO.	FUNCTION NAME	OPERATION
		Transporting Payload in Shuttle

MISSION PHASE/EVENT	REQUIREMENT ALLOCATION

TITLE:

GUIDELINE

POTENTIAL HAZARD:

REMARKS/INTEGRATION CONSIDERATIONS:

- Augmented hemispherical shield - shielding nearly encompasses the heat source, but has an opening (away from probable source of explosion) that permits radiation of sufficient heat to maintain acceptable heat source temperatures.

An alternative approach that permits the use of lighter and simpler shielding is to increase the separation distance between the heat source and the source of explosion. Blast overpressure and fragment velocities are rapidly reduced as the separation distance increases.

REFERENCES:	CROSS REFERENCES:
CONTRACT NAS 8-26283 DOCUMENTS: SAFETY GUIDELINE NO.	

SAFETY GUIDELINE

NO.	DATE:	REVISION:
RD-5	Sept. 1972	

FUNCTION NO.	FUNCTION NAME	OPERATION
6.4	Survive Pre-Launch Explosion Environment	Survive Fire
5.3	Survive Launch Explosion Environment	
1.3	Survive Uncontrolled Orbiter Re-entry and Impact	

MISSION PHASE/EVENT

Pre-Launch, Launch/Ascent, Re-entry

REQUIREMENT ALLOCATION

Heat Source

TITLE: FIREBALL AND SOLID FIRE PROTECTION

GUIDELINE

A goal of the Heat Source design shall be to withstand the fireball and solid propellant fire which may result from a Shuttle explosion.

POTENTIAL HAZARD:

Solid fire temperatures in the aftermath of a launch pad Shuttle explosion are expected to reach 2600°K (4220° F) and last for a 10-minute duration. Liquid propellant fireball temperatures are expected to reach 2980°K (4900° F) immediately after the explosion and level off to approximately (1250°K) 1800° F in 14 seconds.

REMARKS/INTEGRATION CONSIDERATIONS:

Preliminary analyses of the MHW program indicates that the Fuel Sphere Assemblies will survive these environments.

REFERENCES:

CONTRACT NAS 8-26283

DOCUMENTS: 72SD4201-4-1, Sections 3, 4, 5; Appendix A; 72SD4201-4-2, Appendix A.

SAFETY GUIDELINE NO. RD-105, 72SD4201-5-2.

CROSS REFERENCES:

RD-4

SAFETY GUIDELINE

NO.	DATE:
RD-6	Sept. 1972
	REVISION:

FUNCTION NO.	FUNCTION NAME
5.0	Launch and Insert into Orbit
4.0	Perform Orbital Payload Checkout
3.0	Transfer Payload in Orbit
1.4	Perform Shuttle Orbiter Re-entry
1.5	Perform Shuttle Orbiter Landing

OPERATION

Transporting Payload in Shuttle

MISSION PHASE/EVENT

Pre-launch, Launch/Ascent; On Orbit, Ops. Recovery

REQUIREMENT ALLOCATION

Shuttle Payload Integration and/or Mini-Brayton HSA

TITLE: SHUTTLE CREW: RADIATION EXPOSURE CONTROL

GUIDELINE

Minimize the crew dose rate from nuclear payload throughout all operations by appropriate separation distances or radiation shielding (maximum allowable of 150 mrem/day from nuclear payload).

POTENTIAL HAZARD:

Radiation exposure to the crew in excess of permissible dose levels.

REMARKS/INTEGRATION CONSIDERATIONS:

The allowable exposure limit currently in use by NASA is a yearly average of 200 mrem/day to the bone marrow (5 cm depth) from all radiation sources. Cosmic, galactic, and trapped radiation contribute approximately 50 mrem/day. Therefore, the Shuttle crew exposure should be minimized to a maximum allowable dose rate from the nuclear payload of 150 mrem/day. The 150 mrem/day maximum allowable dose is based on yearly averages. Since most crew time durations are short, higher dose rates may be permissible for shorter periods of time.

REFERENCES:

CONTRACT NAS 8-26283

DOCUMENTS: 72SD4201-2-1, Section 4.2, Appendix A

SAFETY GUIDELINE NO. GO-134, 75SD4201-5-2.

CROSS REFERENCES:

SAFETY GUIDELINE

NO. RD-7

DATE: Sept. 1972

REVISION:

FUNCTION NO.	FUNCTION NAME
6.0	Perform Pre-Launch & Countdown Ops.
5.2	Perform Launch & Inject Sequence
4.2	Startup and Operate P/L In Shuttle Orbiter
1.4	Perform Shuttle Orbiter Re-entry
1.5	Perform Shuttle Orbiter Landing

OPERATION

Payload Monitoring

MISSION PHASE/EVENT

Pre-Launch, Launch/Ascent, On Orbit Ops, Re-entry, Landing

REQUIREMENT ALLOCATION

Heat Source Assembly and Shuttle

TITLE: PAYLOAD STATUS MONITORING

GUIDELINE

Provide sensors to monitor Heat Source Assembly and Space Shuttle Wall temperature and crew compartment radiation levels. Provide an alarm to warn crew of a potential problem.

POTENTIAL HAZARD:

Overtemperature of Heat Source Assembly could result in Space Shuttle equipment and structure damage or even release of fuel in a runaway condition if HS fuel temperatures were to exceed 2483°K (4010°F)

Overexposure of crew could result from fuel release

REMARKS/INTEGRATION CONSIDERATIONS:

Outputs of monitoring sensors should be displayed in crew compartment and should trigger warning devices in the event of a hazardous situation.

REFERENCES:

CONTRACT NAS 8-26283

DOCUMENTS: 72SD4201-4-1, Section 4, 5

SAFETY GUIDELINE NO. GD-116 (72SD4201-5-2)
GD-123 (72SD4201-5-2)
GD-124 (72SD4201-5-2)

CROSS REFERENCES:

SAFETY GUIDELINE

NO.	DATE:
GD-3	Sept. 1972
	REVISION:

FUNCTION NO.	FUNCTION NAME	OPERATION
7.2 or 7.3 or 7.4 7.5 1.8	Transfer P/L to Pad Transfer P/L to MRF Transfer P/L to VAB Install P/L in P/L Bay & Checkout Remove, Service or Dispose of P/L	Ground Handling and Shuttle/ Mini-Brayton Integration

MISSION PHASE/EVENT

Pre-Launch, Recovery

REQUIREMENT ALLOCATION

Mini-Brayton Support Equipment

TITLE: TRANSFER MODULE

GUIDELINE

Provide a Transfer Module for installation of the Power Module in the Shuttle Payload Bay.

POTENTIAL HAZARD:

Dropping and damaging Mini-Brayton Power Module.

REMARKS/INTEGRATION CONSIDERATIONS:

A transfer module can provide a safe method of handling the payload and mounting it in the Shuttle payload bay. It is a carriage type of assembly in which the Power Module is placed prior to installation in the Shuttle. The key advantage is that required ancillary equipment can be incorporated into the transfer module rather than mounted on the Shuttle; for example, the capability to provide coolant gas during ascent or re-entry could be accomplished by the transfer module. The disadvantage of this approach is the additional weight and volume penalty.

REFERENCES:

CONTRACT NAS 8-26283

DOCUMENTS: 72SD4201-4-1, Sections 3, 4, 5

SAFETY GUIDELINE NO. GD-121 (72SD4201-5-2)

CROSS REFERENCES:

SAFETY GUIDELINE

NO.	DATE:
GO-3	Sept. 1972
	REVISION:

FUNCTION NO.	FUNCTION NAME
7.0	Perform Ground Flow Ops at Launch Fac.
6.0	Perform Pre-Launch & Countdown Ops
1.6	Perform Shuttle Orbiter Safing
1.7	Transfer Shuttle Orbiter to MRF
1.8	Remove, Service or Dispose of P/L

OPERATION

Emergency Retrieval

MISSION PHASE/EVENT

Prelaunch, Recovery

REQUIREMENT ALLOCATION

Mission Planning
(Ground Operations)

TITLE: QUICK RETRIEVAL OPERATIONS

GUIDELINE

Provide quick retrieval operations to remove the Mini-Brayton from the Shuttle during an emergency.

POTENTIAL HAZARD:

The isotope heat source presents a potential risk situation when the Shuttle experiences an emergency such as a fire. This hazard can be reduced by quickly removing the heat source from the Shuttle.

REMARKS/INTEGRATION CONSIDERATIONS:

Consideration should be given to removing the Mini-Brayton power module or individual heat sources.

REFERENCES:

CONTRACT NAS 8-26283

DOCUMENTS: 72SD4201-4-1, Sections 4, 5, 6, Appendix C

SAFETY GUIDELINE NO. GO-118 (72SD4201-5-2)

CROSS REFERENCES:

SAFETY GUIDELINE	NO. GO-4	DATE: Sept. 1972 REVISION:

FUNCTION NO.	FUNCTION NAME	OPERATION
3.1	Transfer Payload from Shuttle	Abort Mission

MISSION PHASE/EVENT	REQUIREMENT ALLOCATION
On Orbit Operations	Mission Planning

TITLE: IN-ORBIT REPAIRS

GUIDELINE

When non-reparable equipment failures preclude placing the nuclear payload in earth orbit, the payload shall be returned to earth by the Shuttle.

POTENTIAL HAZARD:

Random re-entry of the nuclear heat source in less than ten half lives of the isotope fuel.

REMARKS/INTEGRATION CONSIDERATIONS:

It is desirable to recover the nuclear payload and return it to earth rather than either jettisoning the nuclear payload in low earth orbit (for possible recovery at a later date) or boosting the payload to a high earth disposal orbit. Therefore, when in-orbit repairs are unsuccessful, the Shuttle and payload should return to the landing site. The nuclear payload can be stored at the launch/landing site for use at a later date.

REFERENCES:	CROSS REFERENCES:
CONTRACT NAS 8-26283 DOCUMENTS: 72SD 4201-4-1, Section 6 SAFETY GUIDELINE NO. GO-138 (72SD4201-5-2)	